ME571/GEOL571 GEOLOGY AND ECONOMICS OF STRATEGIC AND CRITICAL MINERALS COMMODITIES: REE SPRING 2017

Virginia T. McLemore

Safety Moment

Discussion of SME and papers

one page reports due to me by email

Discussion of papers

Mid-term before or after spring break?

ASSIGNMENT

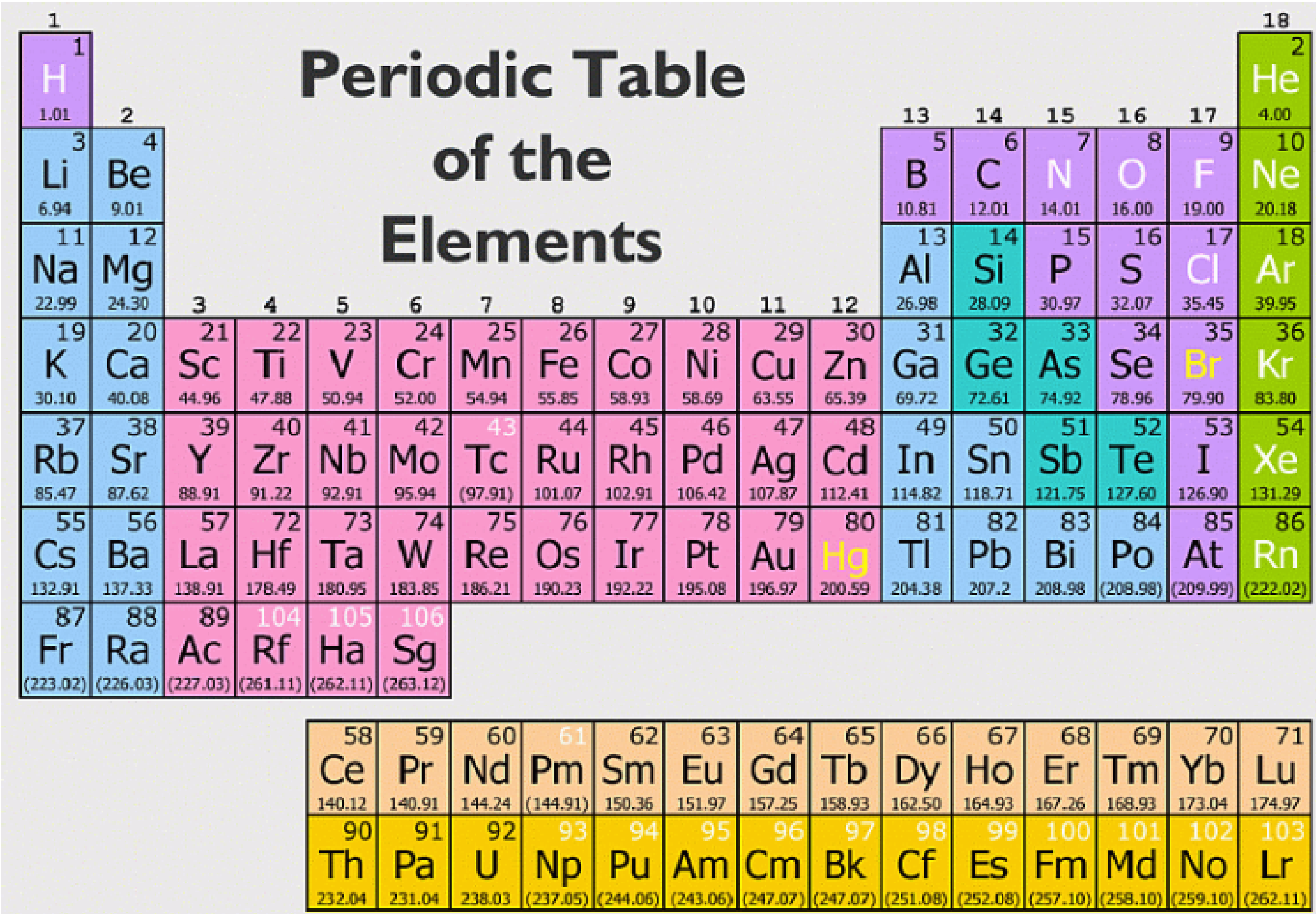
REE Feb 27, March 6

Castor, S.B., 2008, The Mountain Pass rare-earth carbonatite and associated ultrapotassic rocks, California: The Canadian Mineralogist, v. 46, p. 779-806, http://canmin.geoscienceworld.org/content/46/4/779.full.pdf+html?sid=180ae325-acd5-4226-9a02-175f7a865e17

Long, K.R., van Gosen, B.S., Foley, N.K. and Cordier, D., 2010, The principle rare earth elements deposits of the United States—A summary of domestic deposits and a global perspective: U.S. Geological Survey, Scientific Investigations Report 2010-5220, 104 p., http://pubs.usgs.gov/sir/2010/5220/ (accessed 5/1/12).

Mariano and Mariano, 2012, Rare earth mining and exploration in North America: Elements, v. 8, 369-376, http://elements.geoscienceworld.org/content/8/5/369.full.pdf+html?sid=605ebd04-9070-4994-9bce-b1cdd79f349d

INTRODUCTION



Periodic Table of the Elements

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 H 1.01																	2 He 4.00
3 Li 6.94	4 Be 9.01											5 B 10.81	6 C 12.01	7 N 14.01	8 O 16.00	9 F 19.00	10 Ne 20.18
11 Na 22.99	12 Mg 24.30											13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.07	17 Cl 35.45	18 Ar 39.95
19 K 30.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.88	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.85	27 Co 58.93	28 Ni 58.69	29 Cu 63.55	30 Zn 65.39	31 Ga 69.72	32 Ge 72.61	33 As 74.92	34 Se 78.96	35 Br 79.90	36 Kr 83.80
37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.94	43 Tc (97.91)	44 Ru 101.07	45 Rh 102.91	46 Pd 106.42	47 Ag 107.87	48 Cd 112.41	49 In 114.82	50 Sn 118.71	51 Sb 121.75	52 Te 127.60	53 I 126.90	54 Xe 131.29
55 Cs 132.91	56 Ba 137.33	57 La 138.91	72 Hf 178.49	73 Ta 180.95	74 W 183.85	75 Re 186.21	76 Os 190.23	77 Ir 192.22	78 Pt 195.08	79 Au 196.97	80 Hg 200.59	81 Tl 204.38	82 Pb 207.2	83 Bi 208.98	84 Po (208.98)	85 At (209.99)	86 Rn (222.02)
87 Fr (223.02)	88 Ra (226.03)	89 Ac (227.03)	104 Rf (261.11)	105 Ha (262.11)	106 Sg (263.12)												
				58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm (144.91)	62 Sm 150.36	63 Eu 151.97	64 Gd 157.25	65 Tb 158.93	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.04	71 Lu 174.97
				90 Th 232.04	91 Pa 231.04	92 U 238.03	93 Np (237.05)	94 Pu (244.06)	95 Am (243.06)	96 Cm (247.07)	97 Bk (247.07)	98 Cf (251.08)	99 Es (252.08)	100 Fm (257.10)	101 Md (258.10)	102 No (259.10)	103 Lr (262.11)

Figure 1. Periodic table of the elements. The rare earth elements comprise 15 elements, which range in atomic number from 57 to 71, including lanthanum (La) to lutetium (Lu). The elements are also commonly referred to as "lanthanides." Yttrium (Y, atomic number 39) is also typically included with the rare earth elements group because it shares chemical, physical, and application properties with the lanthanides.

http://pubs.usgs.gov/sir/2010/5220/

REE

- Lithophile elements (or elements enriched in the crust)
- Similar physical and chemical properties
- Occur together in nature
- Classified as metals
- Soft, malleable, ductile and usually quite reactive metals
- MP range from 798 to 1663 deg C

57	58	59	60	62	63	64	65	66	67	68	69	70	71	39
La	**Ce**	**Pr**	**Nd**	**Sm**	**Eu**	**Gd**	**Tb**	**Dy**	**Ho**	**Er**	**Tm**	**Yb**	**Lu**	**Y**
138.91	140.12	140.91	144.24	150.36	151.96	157.25	158.93	162.5	164.93	167.26	168.93	173.04	174.97	88.906

Light rare earths | **Heavy rare earths**

La - Lanthanum
Ce - Cerium
Pr - Praseodymium
Nd - Neodymium
Sm - Samarium

Eu - Europium
Gd - Gadolinium
Tb - Terbium
Dy - Dysprosium
Ho - Holmium

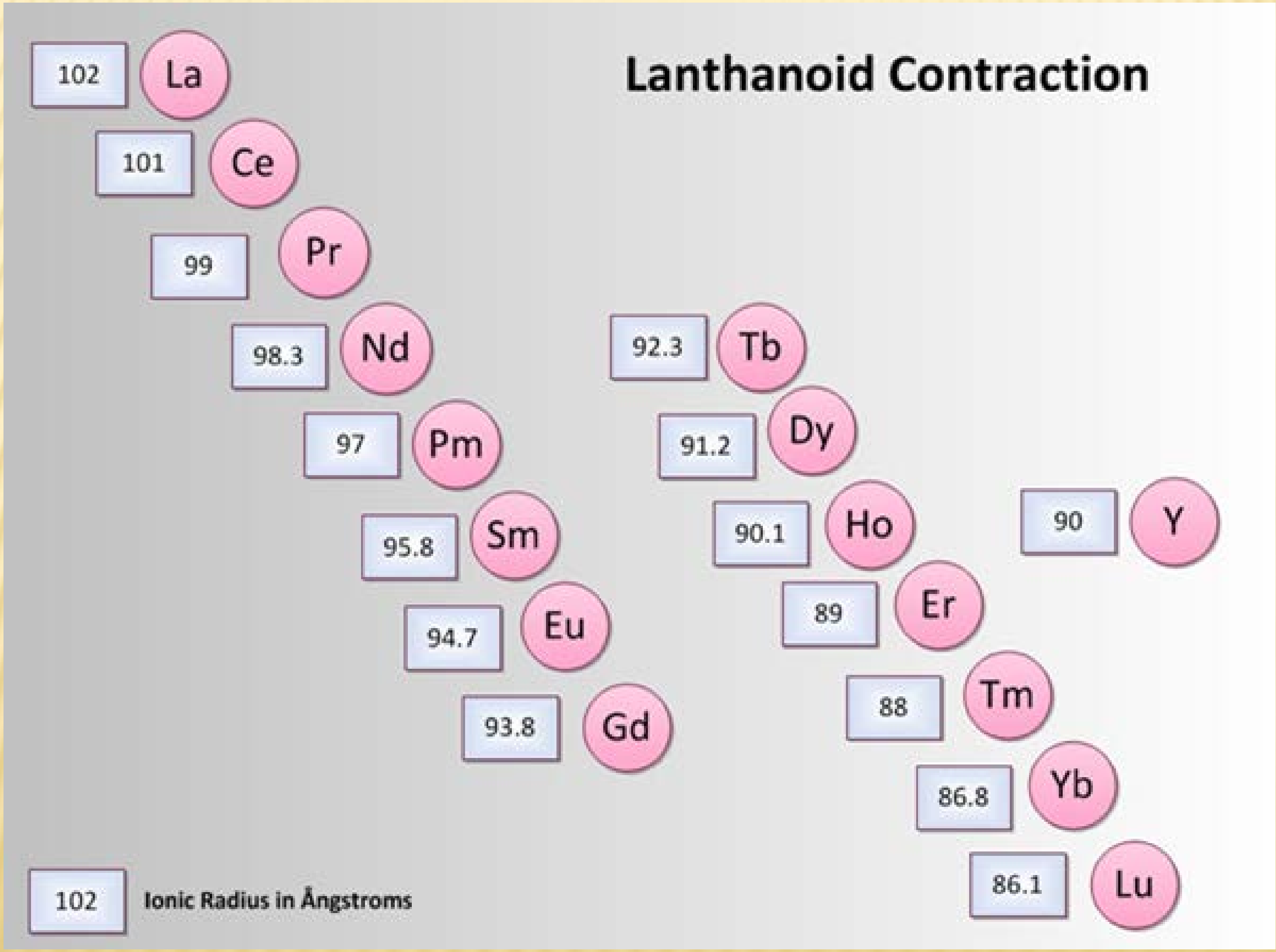
Er - Erbium
Tm - Thulium
Yb - Ytterbium
Lu - Lutetium
Y - Yttrium

Figure 2.2: Sub-groups of the rare-earth metals, per industry (not scientific) norms (sources: TMR, industry sources).

ISSUE

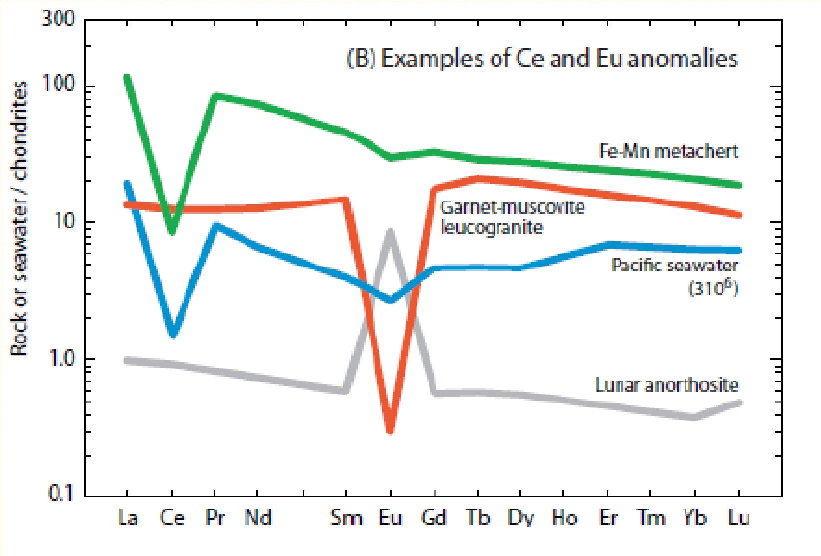
- In 2010, China announced it would significantly restrict REE exports to ensure supply for Chinese domestic manufacturing
- 72% REE export reduction in 2010
- 35% REE export reduction in 2011
- Quota reduction officially to curb rampant and unregulated REE production over the last few years, which has caused significant environmental problems

Ionic radius decreases with increasing number

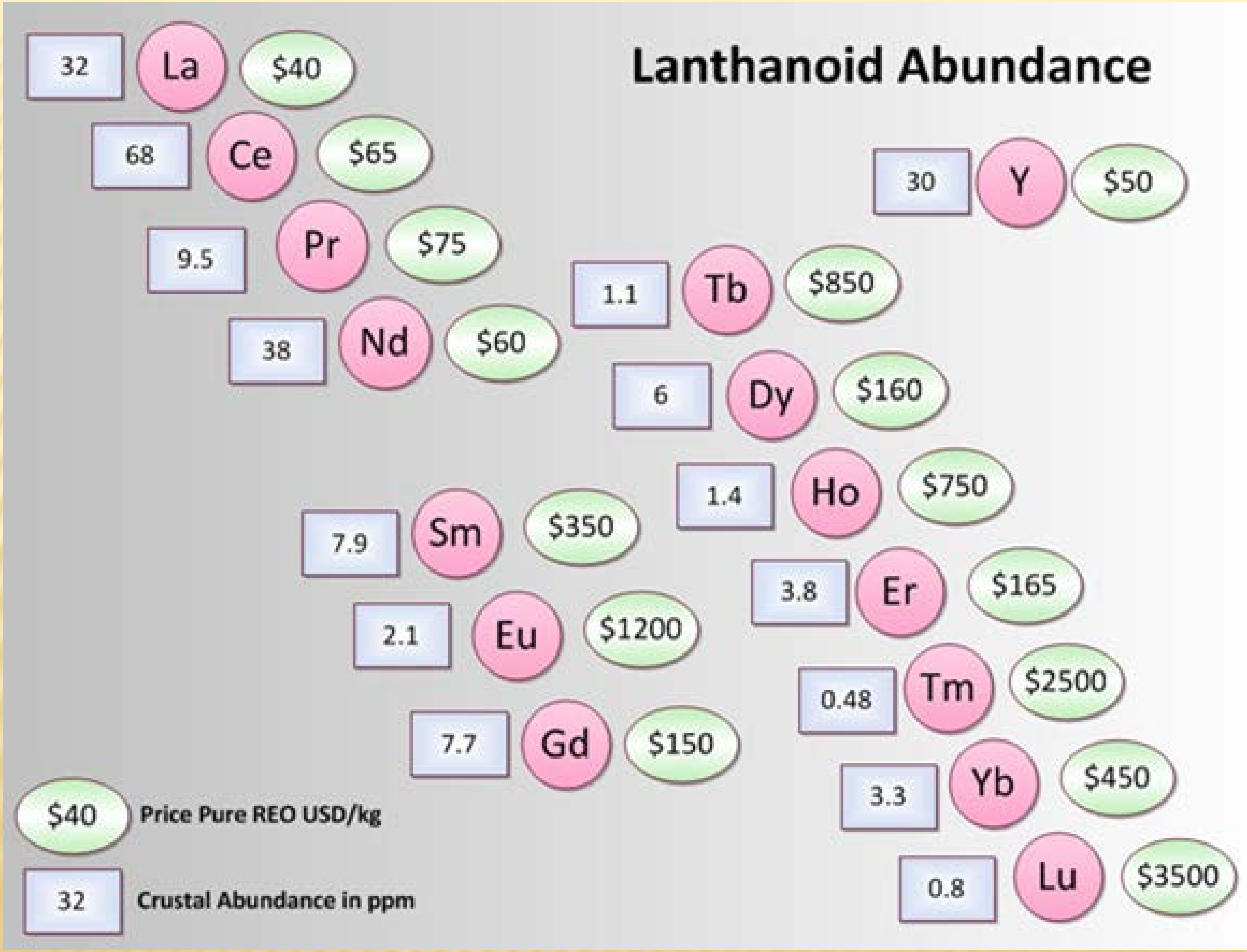


OXIDATION STATE

- All REE occur in 3+ state
- Eu also occurs in 2+ state
  - Substitutes for 2+ cations such as Ca2+
- Ce also occurs in 4+ state
  - insoluble



From: Haxel (2005)


Lanthanoid Abundance
32
La
$40
68
Ce
$65
9.5
Pr
$75
38
Nd
$60
7.9
Sm
$350
2.1
Eu
$1200
7.7
Gd
$150
30
Y
$50
1.1
Tb
$850
6
Dy
$160
1.4
Ho
$750
3.8
Er
$165
0.48
Tm
$2500
3.3
Yb
$450
0.8
Lu
$3500
$40
Price Pure REO USD/kg
32
Crustal Abundance in ppm

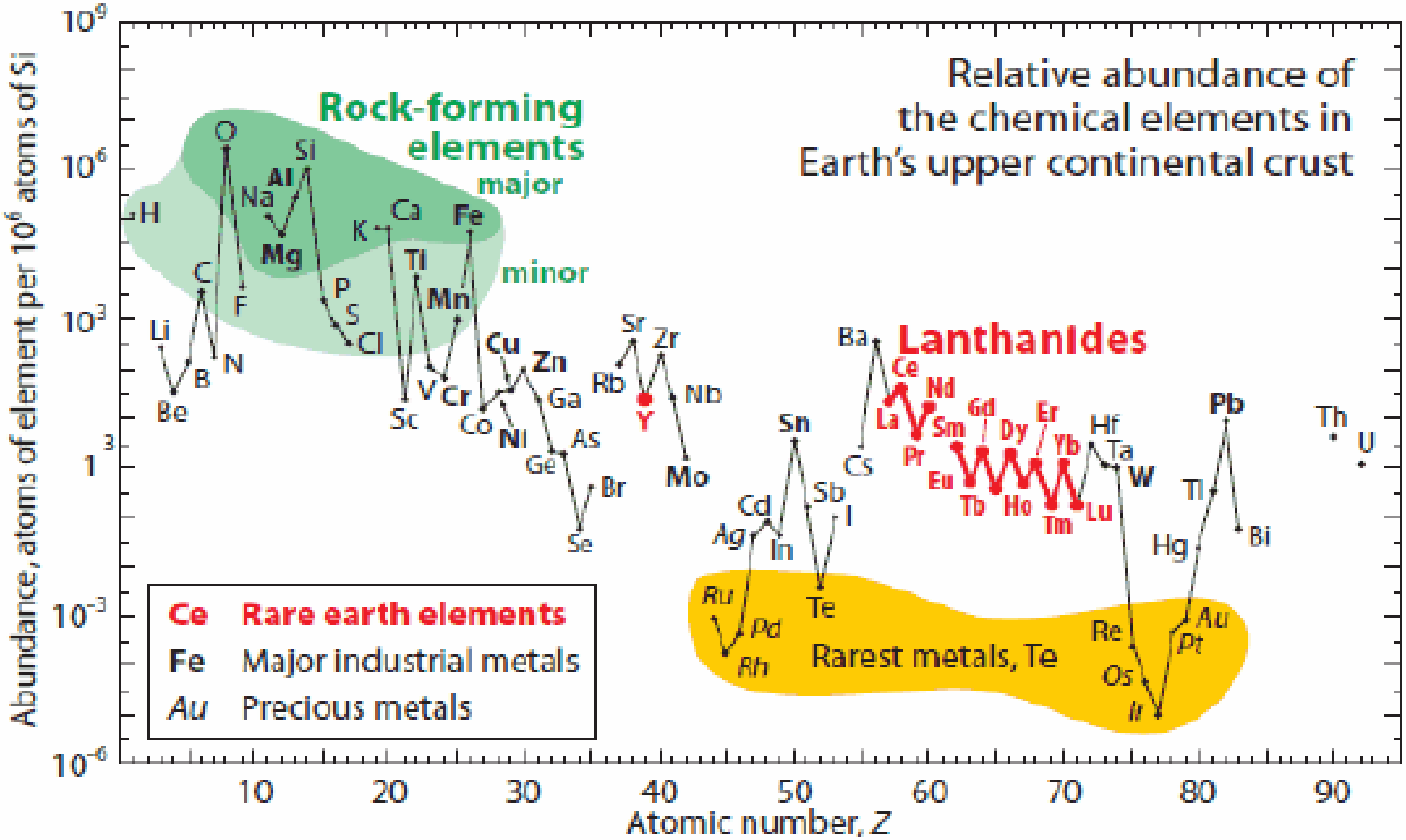


Figure 1 Relative abundance of rare earths (highlighted in red). Figure courtesy of Gordon Haxel, USGS.

- Less abundant than rock forming minerals
- More abundant than precious metals
- Oddo-Harkins rule
  - greater abundance of even-numbered elements relative to their odd-numbered neighbors
- easily smoothed out by “normalizing” the measured concentrations of REEs to some reference REE
  - REE abundances normalized to the primitive mantle values
  - chondritic meteorites

"The estimated average concentration of the rare earth elements in the Earth's crust, which ranges from around 150 to 220 parts per million (table 1), exceeds that of many other metals that are mined on an industrial scale, such as copper (55 parts per million) and zinc (70 parts per million)."

"Although rare earth elements are relatively abundant in the Earth's crust, they are rarely concentrated into mineable ore deposits."

(Long et al., 2010)

Table 1. Estimates of the crustal abundances of rare earth elements.

[Rare earth elements listed in order of increasing atomic number; yttrium (Y) is included with these elements because it shares chemical and physical similarities with the lanthanides. Unit of measure, parts per million]

Rare earth element	Mason and Moore (1982)	Jackson and Christiansen (1993)	Sabot and Maestro (1995)	Wedephol (1995)	Lide (1997)	McGill (1997)
Lanthanum	30	29	18	30	39	5 to 18
Cerium	60	70	46	60	66.5	20 to 46
Praseodynium	8.2	9	5.5	6.7	9.2	3.5 to 5.5
Neodymium	28	37	24	27	41.5	12 to 24
Samarium	6	8	6.5	5.3	7.05	4.5 to 7
Europium	1.2	1.3	0.5	1.3	2	0.14 to 1.1
Gadolinium	5.4	8	6.4	4	6.2	4.5 to 6.4
Terbium	0.9	2.5	0.9	0.65	1.2	0.7 to 1
Dysprosium	3	5	5	3.8	5.2	4.5 to 7.5
Holmium	1.2	1.7	1.2	0.8	1.3	0.7 to 1.2
Erbium	2.8	3.3	4	2.1	3.5	2.5 to 6.5
Thulium	0.5	0.27	0.4	0.3	0.52	0.2 to 1
Ytterbium	3.4	0.33	2.7	2	3.2	2.7 to 8
Lutetium	0.5	0.8	0.8	0.35	0.8	0.8 to 1.7
Yttrium	33	29	28	24	33	28 to 70
Scandium	22		10	16	22	5 to 10
Total	206.1	205.2	159.9	184.3	242.17	

(Long et al., 2010)

REE

Sc

At A Glance: Sc

Atomic Number:	21
Atomic Symbol:	Sc
Atomic Weight:	44.9559
Electron Configuration:	[Ar]4s23d1
Atomic Radius:	216 pm (Van der Waals)
Melting Point:	1541 °C
Boiling Point:	2836 °C
Oxidation States:	3

Sources: It is widely distributed on earth, occurring in very minute quantities in over 800 mineral species.**Uses:** High-intensity lights; tracing agent in refinery crackers for crude oil; highly efficient light source. *Content provided by Los Alamos National Laboratory. Used with permission.*

- 20 kg/yr produce high-intensity lights
- 46Sc used in refinery cracking for crude oil
- Used in mercury vapor lamps (resembles sunlight)
- Recovered from thortveitite or a by-product of U mill tailings

At A Glance: Y	
Atomic Number:	39
Atomic Symbol:	Y
Atomic Weight:	88.9059
Electron Configuration:	[Kr]5s24d1
Atomic Radius:	219 pm (Van der Waals)
Melting Point:	1522 °C
Boiling Point:	3345 °C
Oxidation States:	3

Sources: Improves efficiency of fuels; microwave and cellular communications devices for defense, satellites and phones; jet engine turbines; laser crystals specific to spectral characteristics for military communications; red color in televisions and computer screens. Yttrium stabilized cubic zirconia produces simulated diamonds.
Uses: While yttrium occurs in nearly all of the rare earth minerals, ion-adsorption ores provide the bulk of the world's Yttrium. Recovered commercially from monazite sand, which contains about 3%, and from bastnasite, which contains about 0.2%. Analysis of lunar rock samples obtained during the Apollo missions show a relatively high yttrium content.

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Y

- Yttrium Iron Garnets (YIG) are used as resonators for use in frequency meters, magnetic field measurement devices, tunable transistors Gunn oscillators, cellular communications devices
- stabilizer and mold former for exotic light-weight jet engine turbines and other parts, and as a stabilizer material in rocket nose cones
- Other uses
- Recovered from monazite

At A Glance: La

Atomic Number:	57
Atomic Symbol:	La
Atomic Weight:	138.9055
Electron Configuration:	[Xe]6s25d1
Atomic Radius:	240 pm (Van der Waals)
Melting Point:	918 °C
Boiling Point:	3464 °C
Oxidation States:	2

Sources: Found in rare-earth minerals such as cerite, monazite, allanite, and bastnasite. Monazite and bastnasite are principal ores in which lanthanum occurs in percentages up to 25 percent and 38 percent respectively. **Uses:**hybrid vehicle batteries, fluid cracking catalysts, glass polishing, fuel cells.*Content provided by Los Alamos National Laboratory. Used with permission.*

At A Glance: Ce

Atomic Number:	58
Atomic Symbol:	Ce
Atomic Weight:	140.12
Electron Configuration:	[Xe]6s24f15d1
Atomic Radius:	235 pm (Van der Waals)
Melting Point:	798 °C
Boiling Point:	3,443 °C
Oxidation States:	4,3

Sources: Cerium is the most abundant rare earth element. Monazite and bastnasite ores are presently the more important sources of cerium.**Uses:**Pollution control technologies such as catalytic converters and fuel additives, glass polishing and UV shielding, water filtration, fluorescent lighting.*Content provided by Los Alamos National Laboratory. Used with permission.*

At A Glance: Pr

Atomic Number:	59
Atomic Symbol:	Pr
Atomic Weight:	140.9077
Electron Configuration:	[Xe]6s24f3
Atomic Radius:	239 pm (Van der Waals)
Melting Point:	931 °C
Boiling Point:	3520 °C
Oxidation States:	3

Sources: Monazite and bastnasite are the two principal commercial sources of praseodymium.**Uses:** Paired with neodymium in permanent magnets, also used in photographic filters, airport signal lenses, pigment in ceramic tile and glass, pollution control catalysts.*Content provided by Los Alamos National Laboratory. Used with permission.*

At A Glance: Nd

Atomic Number:	60
Atomic Symbol:	Nd
Atomic Weight:	144.24
Electron Configuration:	[Xe]6s24f4
Atomic Radius:	229 pm (Van der Waals)
Melting Point:	1021 °C
Boiling Point:	3074 °C
Oxidation States:	3

Sources: It is present in significant quantities in the ore minerals monazite and bastnäsite.
Uses: High powered neodymium-iron-boron permanent magnets used in smartphones, computer hard drives, audio speakers, and many other consumer electronics, hybrid and electric vehicle motors, wind turbine generators, MRI machines, and defense equipment; also used in lasers and glass production.
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At A Glance: Pm

Atomic Number:	61
Atomic Symbol:	Pm
Atomic Weight:	145
Electron Configuration:	[Xe]6s24f5
Atomic Radius:	236 pm (Van der Waals)
Melting Point:	1042 °C
Boiling Point:	~3000 °C
Oxidation States:	3, 2

Sources: Promethium is man-made and does not occur in nature.
Uses: Few known uses of promethium.

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At A Glance: Sm

Atomic Number:	62
Atomic Symbol:	Sm
Atomic Weight:	150.4
Electron Configuration:	[Xe]6s24f6
Atomic Radius:	229 pm (Van der Waals)
Melting Point:	1074 °C
Boiling Point:	1794 °C
Oxidation States:	3, 2

Sources: Found along with other rare earth elements in many minerals, including monazite and bastnasite, which are commercial sources. Samarium metal can be produced by reducing the oxide with lanthanum.
Uses: Used in making permanent magnet material that maintains its performance at high temperatures, primarily used in defense-related equipment; also used in optical glass, infrared absorbing glass, and lasers. *Content provided by Los Alamos National Laboratory. Used with permission.*

At A Glance: Eu

Atomic Number:	63
Atomic Symbol:	Eu
Atomic Weight:	151.96
Electron Configuration:	[Xe]6s24f7
Atomic Radius:	233 pm (Van der Waals)
Melting Point:	822 °C
Boiling Point:	1529 °C
Oxidation States:	3, 2

Sources: Bastnasite and monazite are the principal ores containing europium.**Uses:** Phosphors in LCD screens, compact fluorescent lightbulbs, lasers.
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At A Glance: Gd

Atomic Number:	64
Atomic Symbol:	Gd
Atomic Weight:	157.25
Electron Configuration:	[Xe]6s24f75d1
Atomic Radius:	237 pm (Van der Waals)
Melting Point:	1313 °C
Boiling Point:	3273 °C
Oxidation States:	3

Sources: Bastnasite and monazite are the principal ores containing gadolinium.
Uses: Phosphors in television, microwave applications, heat resistant metals and alloys.

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At A Glance: Tb

Atomic Number:	65
Atomic Symbol:	Tb
Atomic Weight:	158.9254
Electron Configuration:	[Xe]6s24f9
Atomic Radius:	221 pm (Van der Waals)
Melting Point:	1356 °C
Boiling Point:	3230 °C
Oxidation States:	3

Sources: Terbium is never found in nature as a free element, but it is contained in many minerals, including cerite, gadolinite, monazite, xenotime and euxenite.**Uses:** Energy efficient fluorescent lighting, magneto-optic recording of data, solid-state devices, and fuel cells.
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At A Glance: Dy

Atomic Number:	66
Atomic Symbol:	Dy
Atomic Weight:	162.50
Electron Configuration:	[Xe]6s24f10
Atomic Radius:	229 pm (Van der Waals)
Melting Point:	1413 °C
Boiling Point:	2567 °C
Oxidation States:	3

Uses:A key additive to NdFeB magnets to maintain their magnetic properties at high temperatures; consumer electronics.*Content provided by Los Alamos National Laboratory. Used with permission.*

At A Glance: Ho

Atomic Number:	67
Atomic Symbol:	Ho
Atomic Weight:	164.9304
Electron Configuration:	[Xe]6s24f11
Atomic Radius:	216 pm (Van der Waals)
Melting Point:	1474 °C
Boiling Point:	2700 °C
Oxidation States:	3

Sources: Holmium is found in the minerals monazite and gadolinite, and is usually commercially extracted from monazite using ion exchange techniques.
Uses: Holmium is one of the least abundant Rare Earth elements and has few commercial uses.

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At A Glance: Er

Atomic Number:	68
Atomic Symbol:	Er
Atomic Weight:	167.26
Electron Configuration:	[Xe]6s24f12
Atomic Radius:	235 pm (Van der Waals)
Melting Point:	1529 °C
Boiling Point:	2868 °C
Oxidation States:	

Uses: Fiber optic data transmission, lasers for medical and dental uses, glass coloration used in sunglasses and decorative crystal glassware. *Content provided by Los Alamos National Laboratory. Used with permission.*

At A Glance: Tm

Atomic Number:	69
Atomic Symbol:	Tm
Atomic Weight:	168.9342
Electron Configuration:	[Xe]6s24f13
Atomic Radius:	227 pm (Van der Waals)
Melting Point:	1545 °C
Boiling Point:	1950 °C
Oxidation States:	3, 2

Sources: The element is never found in nature in pure form, but it is found in small quantities in minerals with other rare earths.**Uses:** Because of the relatively high price of the metal, thulium has not yet found many practical applications.*Content provided by Los Alamos National Laboratory. Used with permission.*

At A Glance: Yb

Atomic Number:	70
Atomic Symbol:	Yb
Atomic Weight:	173.04
Electron Configuration:	[Xe]6s24f14
Atomic Radius:	242 pm (Van der Waals)
Melting Point:	819 °C
Boiling Point:	1196 °C
Oxidation States:	3, 2

Sources: A soft silvery metallic element, ytterbium is a rare earth element of the lanthanide series and is found in the minerals gadolinite, monazite, and xenotime.**Uses:** Improves the grain refinement, strength, and other mechanical properties of stainless steel. *Content provided by Los Alamos National Laboratory. Used with permission.*

At A Glance: Lu

Atomic Number:	71
Atomic Symbol:	Lu
Atomic Weight:	174.97
Electron Configuration:	[Xe]6s24f145d1
Atomic Radius:	221 pm (Van der Waals)
Melting Point:	1663 °C
Boiling Point:	3402 °C
Oxidation States:	3

Sources: Found with almost all other rare-earth metals but never by itself, lutetium is very difficult to separate from other elements.**Uses:** Catalysts in cracking, alkylation, hydrogenation, and polymerization; detectors in positron emission tomography (PET). Virtually no other commercial uses have been found yet for lutetium. *Content provided by Los Alamos National Laboratory. Used with permission.*

GOVERNMENT DOCUMENTS

USGS
science for a changing world

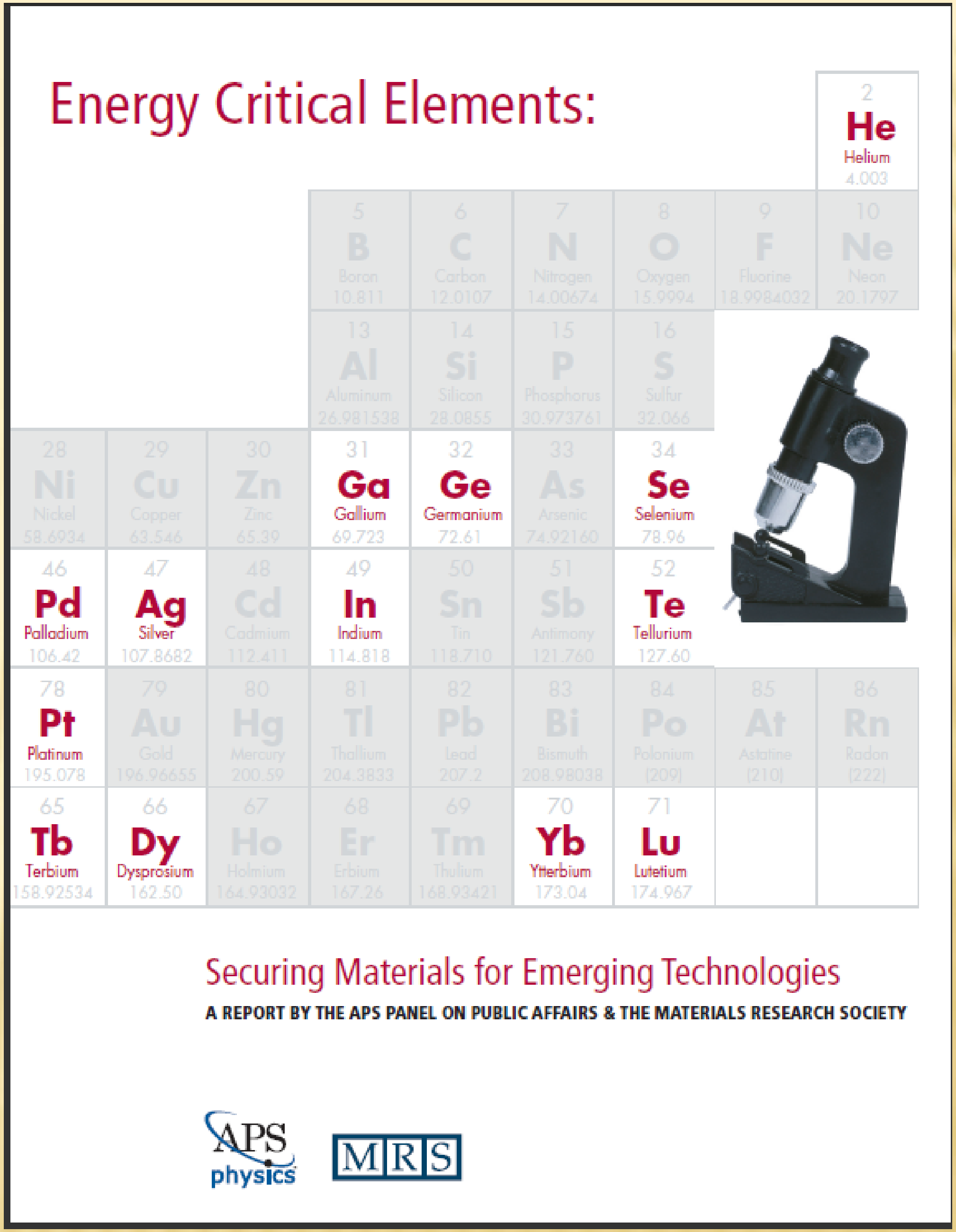
2014 Minerals Yearbook

RARE EARTHS [ADVANCE RELEASE]

U.S. Department of the Interior
U.S. Geological Survey

December 2016

https://minerals.usgs.gov/minerals/pubs/commodity/rare_earths/myb1-2014-raree.pdf



http://www.aps.org/policy/reports/popa-reports/loader.cfm?csModule=security/getfile&PageID=236337

Congressional Research Service

Rare Earth Elements: The Global Supply Chain

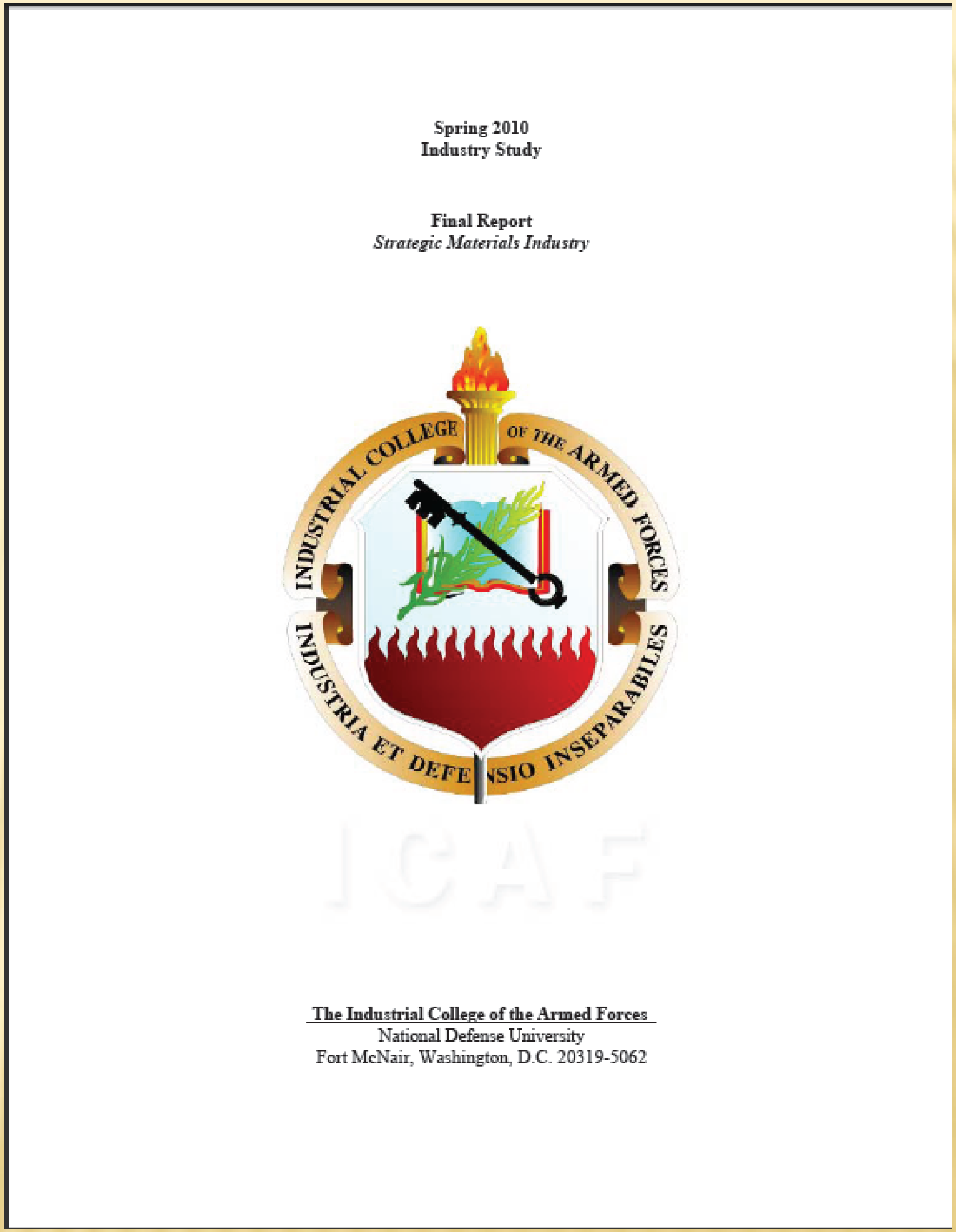
Marc Humphries
Specialist in Energy Policy

June 8, 2012

Congressional Research Service
7-5700
www.crs.gov
R41347

CRS Report for Congress
Prepared for Members and Committees of Congress

http://www.fas.org/sgp/crs/natsec/R41347.pdf



Spring 2010
Industry Study

Final Report
Strategic Materials Industry

INDUSTRIAL COLLEGE OF THE ARMED FORCES
INDUSTRIA ET DEFENSIO INSEPARABILES

ICAF

The Industrial College of the Armed Forces
National Defense University
Fort McNair, Washington, D.C. 20319-5062

http://www.ndu.edu/es/programs/academic/industry/reports/2010/pdf/icaf-is-report-strategic-mat-2010.pdf

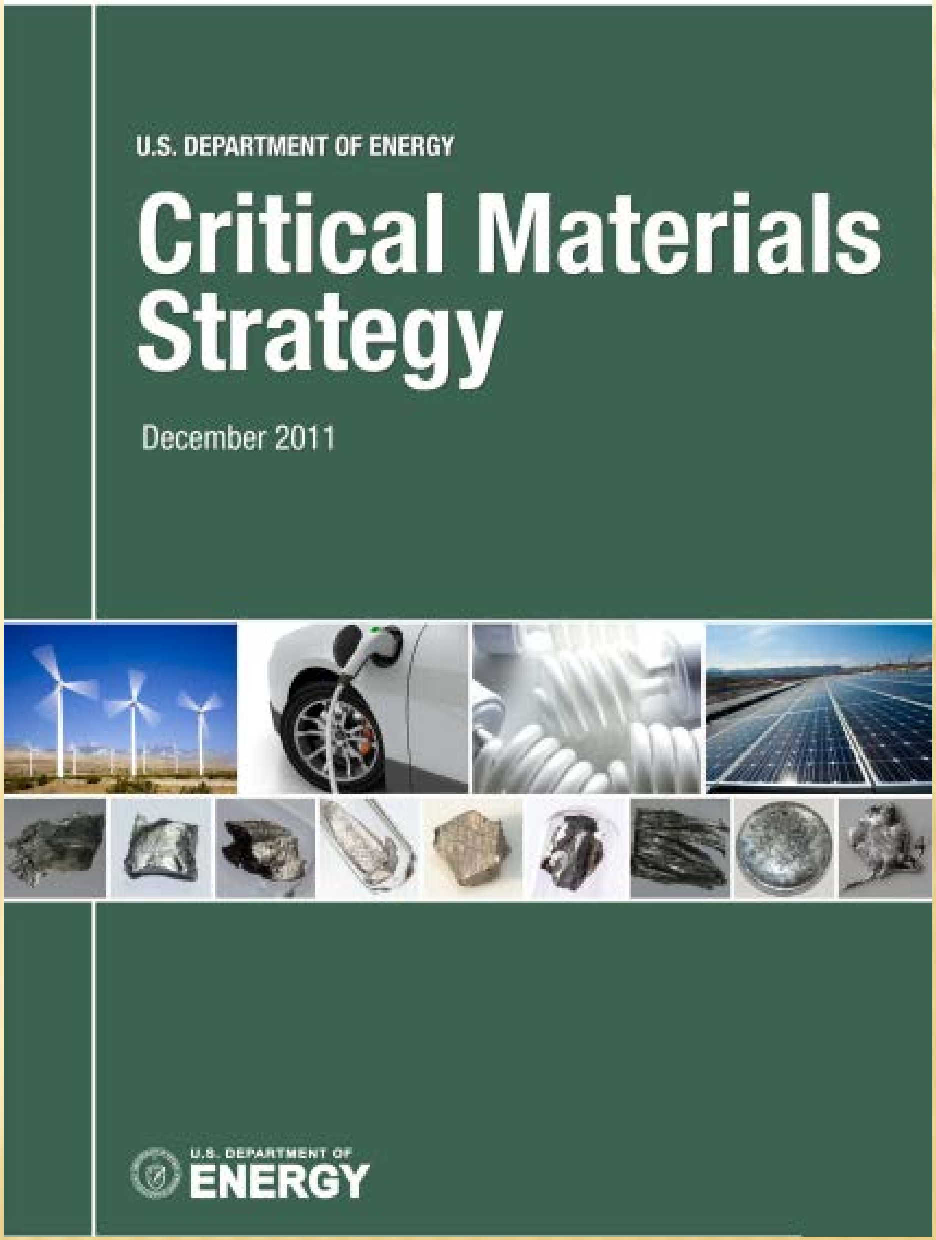
GAO

Accountability * Integrity * Reliability

Rare Earth Materials in the Defense Supply Chain

Briefing for Congressional Committees
April 1, 2010

http://www.gao.gov/new.items/d10617r.pdf



http://energy.gov/sites/prod/files/DOE_CMS2011_FINAL_Full.pdf

British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Rare Earth Elements

November 2011

Definitions, mineralogy and deposits

Definitions and characteristics

The rare earth elements (REE) (sometimes referred to as the rare earth metals) are a group of 17 chemically similar metallic elements, including the 15 lanthanides, scandium and yttrium. The lanthanides are elements spanning atomic numbers 57 (lanthanum, La) to 71 (lutetium, Lu) (Table 1). The lanthanides all occur in nature, although promethium[1], the rarest, only occurs in trace quantities in natural materials as it has no long-lived or stable isotopes (Castor and Hedrick, 2006). Scandium and yttrium are considered REE as they have similar chemical and physical properties. Separation of the individual REE was a difficult challenge for chemists in the 18th and 19th centuries, and consequently it was not until the 20th century that they were all identified. On account of their chemical similarity the REE can very easily substitute for one another making refinement to pure metal difficult.

The term rare earth is a misnomer arising from the rarity of the minerals from which they were originally isolated (Figures 1 and 2). In contrast REEs are relatively plentiful in the Earth's crust having an overall crustal abundance of 9.2 ppm (Rudnick et al. 2003). The crustal abundance of individual REE varies widely, from cerium the most abundant at 43 ppm (exceeding other important metals including copper — 27 ppm and lead — 11 ppm) to 0.28 ppm for thulium (Taylor and McLennan, 1985; Rudnick et al. 2003).

The lanthanides are commonly divided into: lower atomic weight elements, lanthanum through to europium, referred to as the light rare earth elements (LREE) and the heavy rare earth elements (HREE) — gadolinium through to lutetium and yttrium (Table 1). Yttrium is usually grouped with the HREE because of its chemical similarity. The division is somewhat arbitrary and the term middle REE (MREE) is sometimes used to refer to those elements between europium to dysprosium (Samson and Wood, 2004). The relative abundance of the REE varies

1 Promethium is a radioactive element.

Element	Symbol	Atomic number	Atomic weight	Density (gcm^{-3})	Melting Point (°C)	Vicker's hardness, (10 kg load, kg/mm^2)
Scandium	Sc	21	44.95	2.989	1541	85
Yttrium	Y	39	88.90	4.469	1522	38
Lanthanum	La	57	138.90	6.146	918	37
Cerium	Ce	58	140.11	6.160	798	24
Praseodymium	Pr	59	140.90	6.773	931	37
Neodymium	Nd	60	144.24	7.008	1021	35
Promethium[1]	Pm	61	145.00	7.264	1042	-
Samarium	Sm	62	150.36	7.520	1074	45
Europium	Eu	63	151.96	5.244	822	17
Gadolinium	Gd	64	157.25	7.901	1313	57
Terbium	Tb	65	158.92	8.230	1356	46
Dysprosium	Dy	66	162.50	8.551	1412	42
Holmium	Ho	67	164.93	8.795	1474	42
Erbium	Er	68	167.26	9.066	1529	44
Thulium	Tm	69	168.93	9.321	1545	48
Ytterbium	Yb	70	173.04	6.966	819	21
Lutetium	Lu	71	174.97	9.841	1663	77

Table 1 Selected properties of the REE. Compiled from Gupta and Krishnamurthy (2005).

Figure 1 Elongate prismatic fergusonite in an open cavity associated with albite and quartz, Arran, Scotland. Photograph: Fergus MacTaggart, BGS © NERC.

http://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=7&ved=0CHAQFjAG&url=http%3A%2F%2Fwww.bgs.ac.uk%2Fdownloads%2Fstart.cfm%3Fid%3D1638&ei=PbwvUd3IMOryigK-g4DYAg&usg=AFQjCNHv3zX_vBeh3VCZkL5RYzQyWymvBg&sig2=N4NSi7WNik2vt_XKY_2dfA

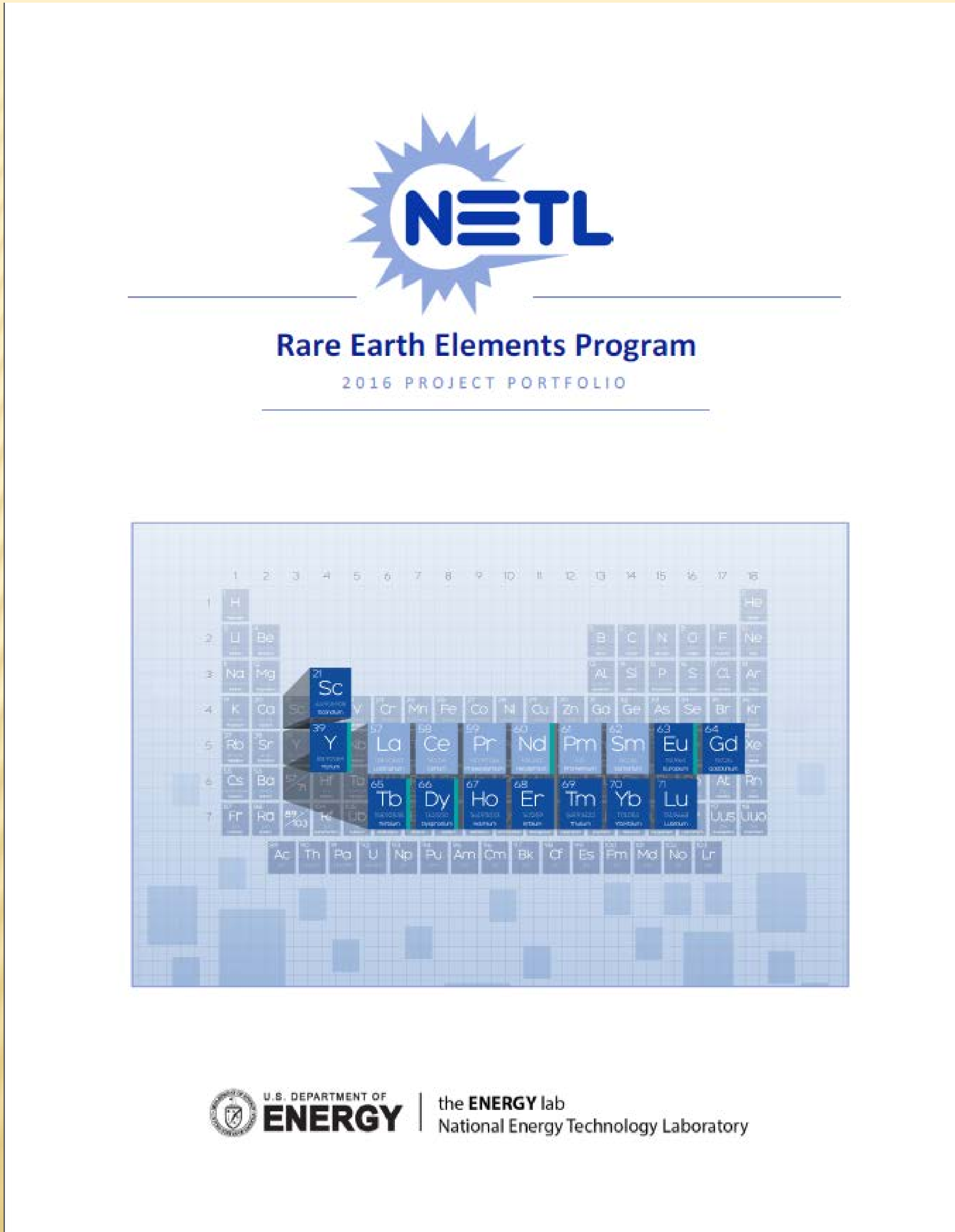
USGS
science for a changing world

The Principal Rare Earth Elements Deposits of the United States—A Summary of Domestic Deposits and a Global Perspective

Scientific Investigations Report 2010–5220

U.S. Department of the Interior
U.S. Geological Survey

http://pubs.usgs.gov/sir/2010/5220/


NETL

Rare Earth Elements Program

2016 PROJECT PORTFOLIO

U.S. DEPARTMENT OF ENERGY | the ENERGY lab National Energy Technology Laboratory

https://www.netl.doe.gov/File%20Library/Research/Coal/Rare%20Earth%20Elements/REE-Project-Portfolio-2016.pdf

USES

- 1970s: Rare earth mineral concentrates.
- 1980s: Mixed rare earth chemical concentrates.
- Early1990s: Separated rare earth oxides and metals.
- Late 1990s: Magnets, phosphors, polishing powders.
- 2000s: Electric motors, computers, batteries, LCDs, mobile phones.

Off Road Vehicles

Electric Diesels

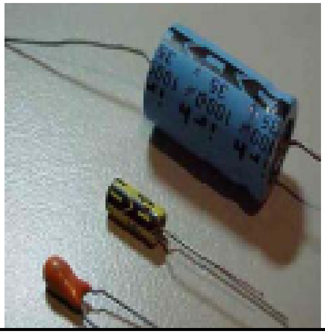
Electric Motor Scooters

JSF and More Electric Aircraft

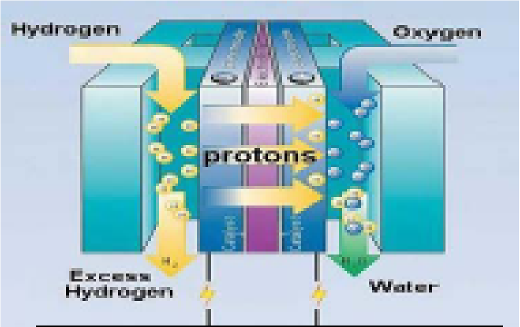
CHPS Future Combat Systems

Zumwalt DDG 1000

Maglev Trains

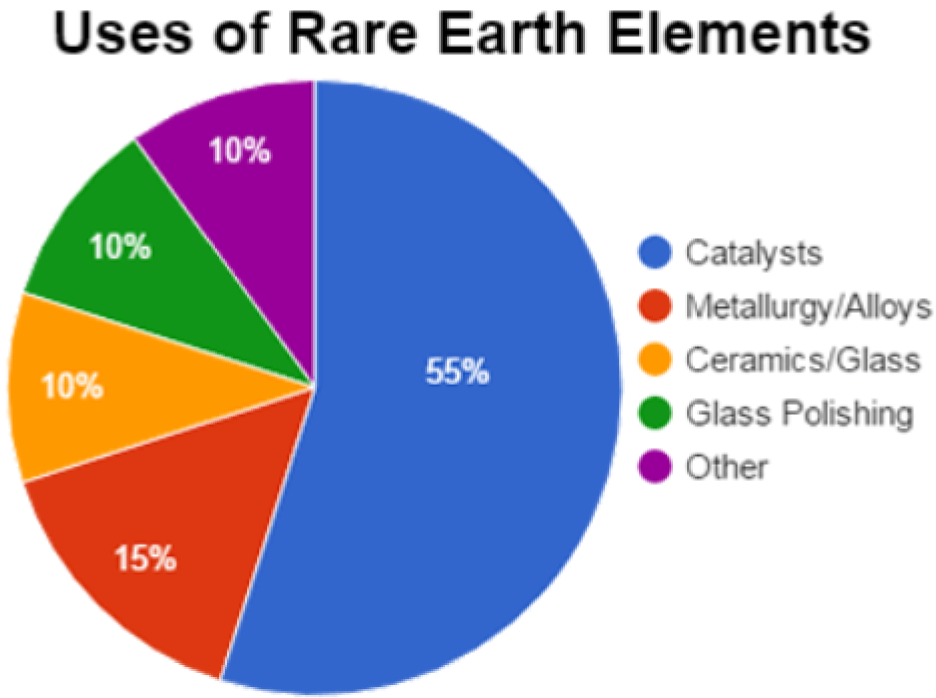


High Energy Density Capacitors



Fuel Cell Systems

REE are so important because each atom of these elements is able to readily give up or accept electrons, which is an important property required to allow magnets, optics, electronics and other applications to work.



Uses in the United States as reported by the United States Geological Survey Mineral Commodity Summary, 2017

Uses of rare earth elements: This chart shows the use of rare earth elements in the United States during 2013. Many vehicles use rare earth catalysts in their exhaust systems for air pollution control. A large number of alloys are made more durable by the addition of rare earth metals. Glass, granite, marble, and gemstones are often polished with cerium oxide powder. Many motors and generators contain magnets made with rare earth elements. Phosphors used in digital displays, monitors, and televisions are created with rare earth oxides. Most computer, cell phone, and electric vehicle batteries are made with rare earth metals.

Table 2. Examples of common applications of rare-earth elements.

Application	Chemical element[1]																
	Sc	Y	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Alloys and metallurgical uses	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X
Batteries			X	X	X	X	X				X						
Catalysts		X	X	X	X	X		X		X							X
Ceramics	X	X	X	X	X	X		X	X	X		X	X	X	X		X
Electronics		X	X	X	X	X					X	X		X			
Fertilizers			X	X		X											
Glass	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X
Lamps	X	X	X	X	X			X	X		X	X	X	X	X		
Lasers	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Magnets				X	X	X		X	X	X	X	X	X				
Medical and pharmaceutical uses			X	X		X		X	X	X			X	X			X
Neutron absorption		X		X				X	X	X		X	X	X			
Phosphors	X	X	X	X			X	X	X	X	X	X	X	X	X	X	X

[1]The symbols used for chemical elements in this table include the following (in order of atomic number): Sc, scandium; Y, yttrium, La, lanthanum; Ce, cerium; Pr, praseodymium; Nd, neodymium; Pm, promethium; Sm, samarium; Eu, europium; Gd, gadolinium; Tb, terbium; Dy, dysprosium; Ho, holmium; Er, erbium; Tm, thulium; Yb, ytterbium; and Lu, lutetium.

https://pubs.usgs.gov/of/2013/1072/OFR2013-1072.pdf

USES

- Chemical—unique electron configuration
- Catalytic—O storage and release
- Magnetic—high magnetic anisotropy and large magnetic moment
- Optical—fluorescence, high refractive index
- Electrical—high conductivity
- Metallurgical—efficient H storage in REE alloys

REE can not be substituted in most applications

USES THAT DEPEND UPON VALENCE AND SIZE

Mixed rare earths

- Petroleum cracking catalyst (also La, Ce)
- Mischmetal
  - lighter flints
  - alloy additive

Individual rare earth elements

- Nickel-metal(La)-hydride batteries
- Alloying agent (La, Ce, Nd, Y)

USES THAT DEPEND ON 4*f* ELECTRONS

Permanent Magnets

Nd, Pr, Sm, Dy

Phosphors

Eu (red, blue)

Tb (green)

fluorescent lamps

optical displays (TV, etc.)

Fiber optics

Er

USES THAT DEPEND ON THE ABSENCE OF ELECTRONIC TRANSITIONS IN UV, OPTICAL AND IR WAVE LENGTHS

Optical lenses

La, Gd, Lu

Phosphor hosts

Y, Gd

Artificial gem stones

Y

USES THAT DEPEND UPON VALENCE CHANGES

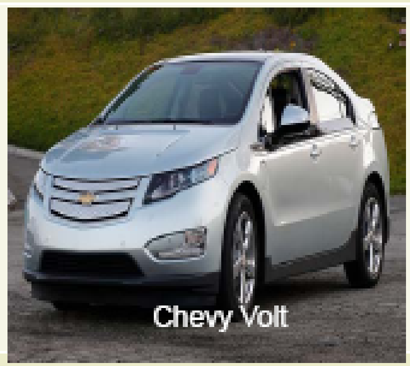
$Ce^{3+} \leftrightarrow Ce^{4+}$ $4f^1 \leftrightarrow 4f^0$

Automotive 3-way emission catalysts

UV light absorption

Polishing compounds

CLEAN ENERGY

Applications		Typical Quantity of REO per unit
Traditional – disc drives, personal electronic devices, etc.		Grams
Hybrid and electric vehicles – direct drives and electric assist motors		Kilograms
Direct Drive Wind Turbines		Metric Ton

http://www.reitausa.org/storage/Challenges%20Facing%20New%20Global%20Rare%20Earth%20Separation%20Plants.pdf

Toyota Prius

2.2 lbs Nd in magnets

22-33 lbs La in batteries

http://www.molycorp.com/hybrid_ev.asp

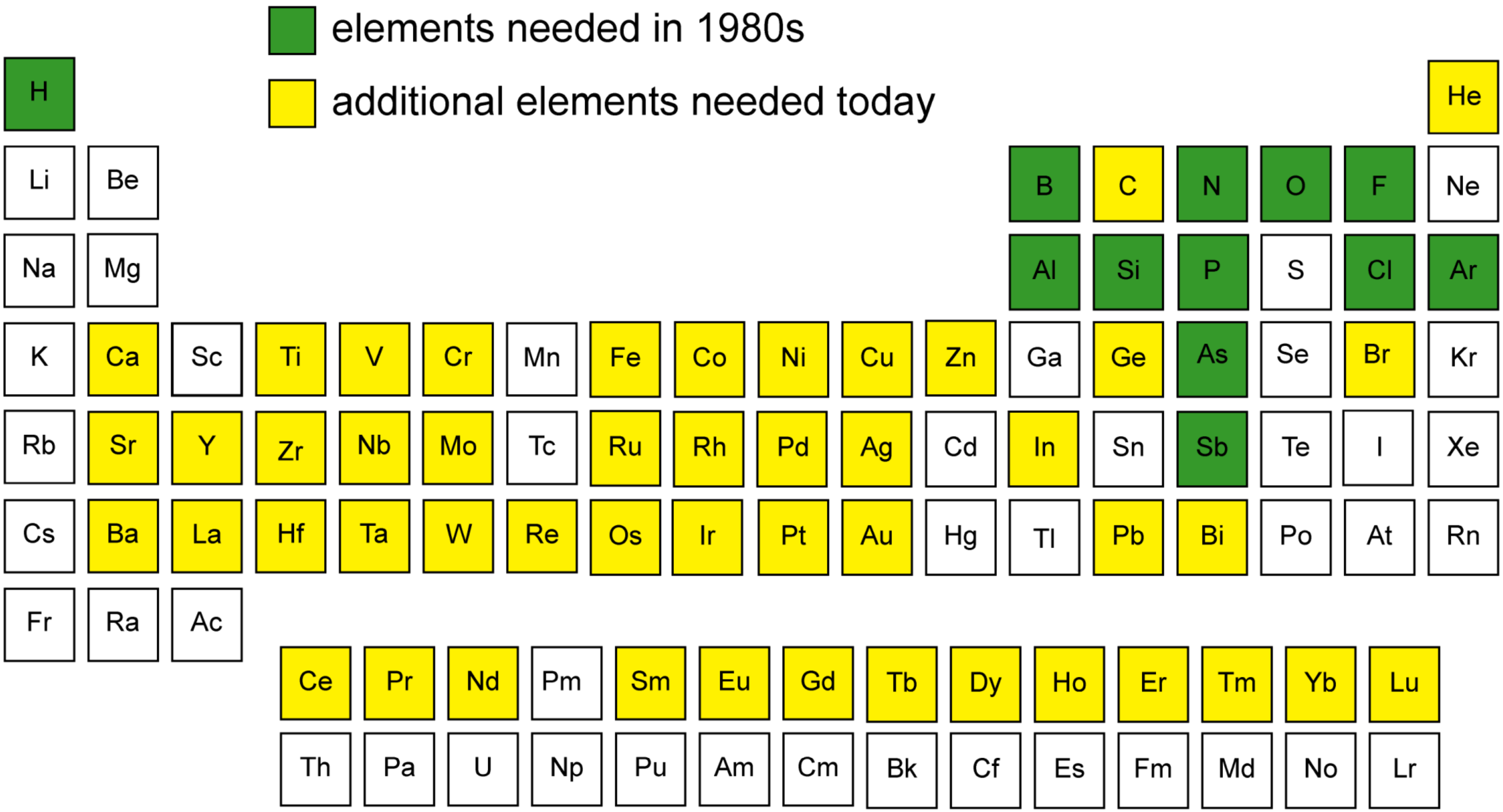
ENABLING DIGITAL TECHNOLOGY

Demand of Rare Earths for Phosphors and Polishing Powders:

Tonnes per annum	2004	2005	AAGR% 2005-10	2010
Total REO Consumption Phosphors	3,652	4,007	13.0%	7,512
Total REO Consumption Polishing Powders	14,100	15,150	9.2%	23,500
AAGR is the Annual Average Growth Rate				

http://www.lynascorp.com/Pages/what-are-rare-earths.aspx

Elements in Computer Chips
(National Research Council, 2007)

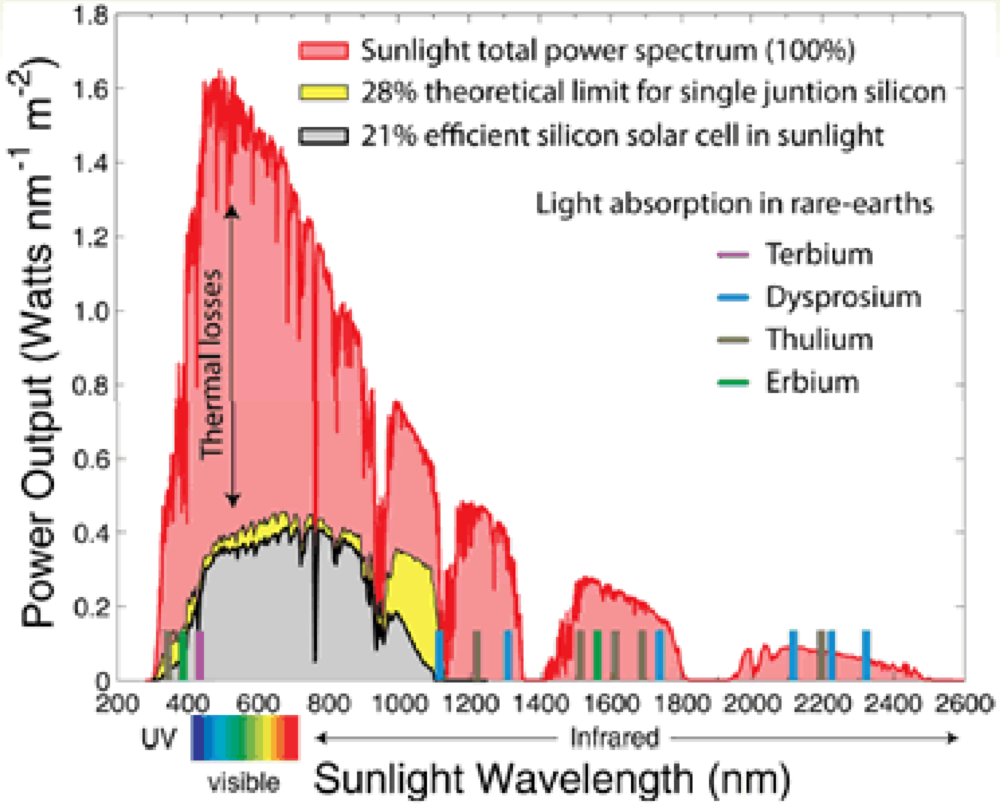


IMPROVING ENERGY EFFICIENCY

Fluid Cracking Catalysts (FCC) are used in the refining operation of crude oil and is the major contributor to “value-add” in the refining process. The process enables the transformation of heavy molecules into lighter compounds that make up gasoline and other fuels such as gas, jet fuel and diesel.

Application	Rare Earths	Demand Drivers
Magnets	**Nd, Pr,** Sm, Tb Dy	Drives for computers, mobile phones, mp3 players, cameras. Hybrid vehicle electric motors. Electric motors for luxury vehicles. Mag-lev trains.
LaNiH Batteries	**La,** Ce, Pr, Nd	Hybrid vehicle batteries. Hydrogen absorption alloys for re-chargeable batteries
Phosphors	**Eu, Y, Tb,** La, Dy, Ce, Pr, Gd	LCDs. PDPs. LEDs. Energy efficient fluorescent lights/lamps.
Fluid Cracking Catalysts	**La,** Ce, Pr, Nd	Petroleum production – greater consumption by 'heavy' oils and tar sands
Polishing Powders	**Ce,** La, Nd	Mechano-chemical polishing powders for TVs, monitors, mirrors and (in nano-particulate from) silicon chips.
Auto Catalysts	**Ce,** La, Nd	Tighter NO_x and SO_2 standards – platinum is re-cycled, but for rare earths it is not economic
Glass Additive	**Ce, La,** Nd, Er	Cerium cuts down transmission of uv light. La increases glass refractive index for digital camera lens.
Fibre Optics	**Er,** Y, Tb, Eu	Signal amplification

SOLAR POWER OUTPUT VS SOLAR SPECTRUM



- Conventional Silicon solar cell conversion limited to a small window of solar photon energies close to the band-gap energy of silicon – single junction limitation
- Using patented 'rare earth oxide' materials → conversion efficiency increased by harnessing a far greater fraction of available energy in the solar spectrum

http://www.australianrareearths.com/what-are-rare-earths.html

China: world's leading consumer? (Brown, 2005).

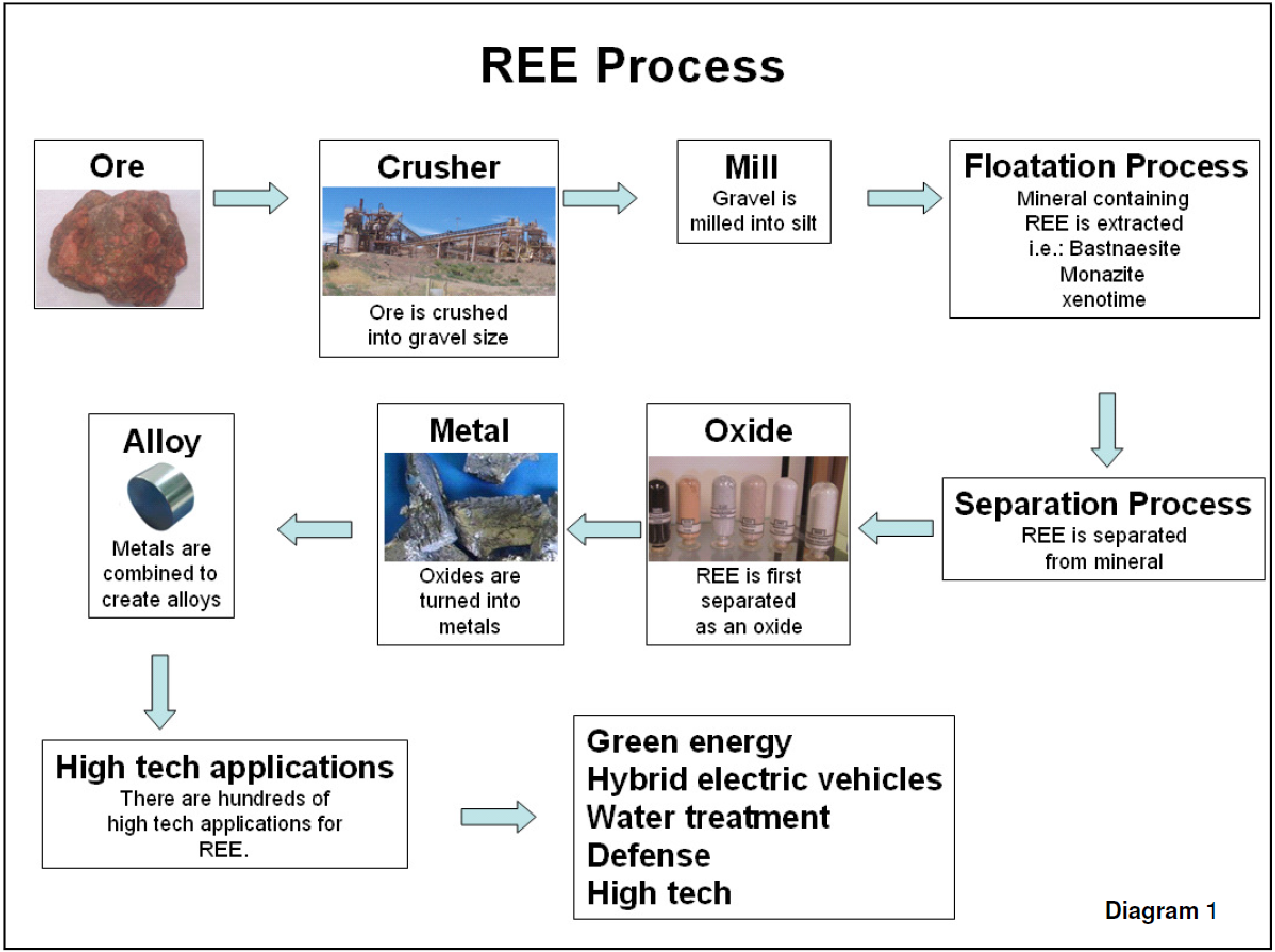
Cell phones — 7 million (1996) to 269 million (2003) in China vs. 44 million (1996) to 159 million (2003) in the United States.

Personal computers and laptops in 2002 — 36 million in China vs. 190 million in the United States, but China's number doubles every 28 months.

Televisions — 374 million in China vs. 243 million in the United States in 2000.

Refrigerators — China surpassed the United States in 2000.

Cars — 24 million in China vs. 226 million in the United States in 2003.



http://fmso.leavenworth.army.mil/documents/rareearth.pdf

HOW MUCH REE ARE NEEDED?

Table 3. Estimated weight (in metric tons) of rare-earth oxides contained in selected manufactured products that entered service in the United States in 2010 and in material containing rare-earth metals that was imported into the United States in 2010.

[Estimates are rounded to two significant figures. t, metric tons; dashes (--), no data; Do., ditto.; LED, light-emitting diode; OEM, original equipment manufacturer. Rare-earth oxides: CeO_2, cerium oxide; Dy_2O_3, dysprosium oxide; Er_2O_3, erbium oxide; Eu_2O_3, europium oxide; Gd_2O_3, gadolinium oxide; La_2O_3, lanthanum oxide; Lu_2O_3, lutetium oxide; Nd_2O_3, neodymium oxide; Pr_6O_{11}, praseodymium oxide; Sm_2O_3, samarium oxide; Tb_4O_7, terbium oxide; Y_2O_3, yttrium oxide]

General application	Product	CeO_2	Dy_2O_3	Er_2O_3	Eu_2O_3	Gd_2O_3	La_2O_3	Lu_2O_3	Nd_2O_3	Pr_6O_{11}	Sm_2O_3	Tb_4O_7	Y_2O_3	Undetermined rare-earth oxides
Mass of compound in manufactured products that entered service in 2010, in metric tons														
Alloys	Zinc-based coatings for light-gage steel supports[1]	5.6	--	--	--	--	2.4	--	--	--	--	--	--	--
Batteries	Electric and hybrid vehicles		--	--	--	--	4,000	--	--	--	--	--	--	--
Catalysts	Automotive catalytic converters	1,400	--	--	--	--		--	--	--	--	--	--	--
Do.	Fluid catalytic cracking (FCC) catalysts for petroleum refining	210	--	--	--	--	3,400	--	640	--	--	--	--	--
Magnets	Automotive (general applications)	--	4.5	--	--	--	--	--	76	--	--	--	--	--
Do.	Cell phone and other mobile devices	--	--	--	--	--	--	--	86	4.2	--	--	--	--
Do.	Electric and hybrid vehicle motors	--	40	--	--	--	--	--	300	--	--	--	--	--
Do.	Electronic power steering in vehicles	--	--	--	--	--	--	--	26	1.7	--	--	--	--
Do.	External disc drives for servers	--	--	--	--	--	--	--	61	4.2	--	--	--	--
Do.	Game consoles	--	--	--	--	--	--	--	64	4.5	--	--	--	--
Do.	OEM speakers in vehicles	--	--	--	--	--	--	--	7	5	--	--	--	--
Do.	Personal computers and laptops	--	--	--	--	--	--	--	440	30	--	--	--	--

https://pubs.usgs.gov/of/2013/1072/OFR2013-1072.pdf

HOW MUCH REE ARE NEEDED?

Table 3. Estimated weight (in metric tons) of rare-earth oxides contained in selected manufactured products that entered service in the United States in 2010 and in material containing rare-earth metals that was imported into the United States in 2010.—Continued

[Estimates are rounded to two significant figures. t, metric tons; dashes (--), no data; Do., ditto.; LED, light-emitting diode; OEM, original equipment manufacturer. Rare-earth oxides: CeO_2, cerium oxide; Dy_2O_3, dysprosium oxide; Er_2O_3, erbium oxide; Eu_2O_3, europium oxide; Gd_2O_3, gadolinium oxide; La_2O_3, lanthanum oxide; Lu_2O_3, lutetium oxide; Nd_2O_3, neodymium oxide; Pr_6O_{11}, praseodymium oxide; Sm_2O_3, samarium oxide; Tb_4O_7, terbium oxide; Y_2O_3, yttrium oxide]

General application	Product	CeO_2	Dy_2O_3	Er_2O_3	Eu_2O_3	Gd_2O_3	La_2O_3	Lu_2O_3	Nd_2O_3	Pr_6O_{11}	Sm_2O_3	Tb_4O_7	Y_2O_3	Undetermined rare-earth oxides
		Mass of compound in manufactured products that entered service in 2010, in metric tons—Continued												
Phosphors	Fluorescent bulbs[2]	130	--	--	50	--	200	--	--	--	--	56	740	--
Phosphors and diodes	LED televisions[3]	0.0057	--	--	0.0049	--	--	--	--	--	--	--	0.11	--
Solutions	Imaging contrast dye	--	--	--	--	23 to 70	--	--	--	--	--	--	--	--
TOTAL		1,700	45		50	23 to 70	7,600		1,700	50		56	740	--
		Mass of compound in materials imported in 2010, in metric tons												
Catalysts, electronics, fuel additives, glass, imaging contrast dyes, magnets, nuclear fuel rods, phosphors, polishing powders, and others	Imported refined metal and oxides, impure, and intermediate products[4, 5]	3,600	25	33	25	80	7,900	27	590	94	8.8	4.2	670	1,500[6]

[1]Includes only GALFAN®, which contains approximately 0.1 percent rare-earth oxide in a hot-dip coat that makes up about 2 percent of the total weight of the steel.

[2]Includes phosphors used in tube-type and compact fluorescent lights.

[3]Estimates are based on the number of LED televisions sold in the United States in 2010 and assumes a 42-inch screen.

[4]Some material may be exported in various forms. Estimate does not include finished products, such as contrast dye.

[5]Based on United Business Media Global Trade Port Import/Export Reporting Service (PIERS) data for 2010.

[6]Based on limited data. The material was assumed to be bastnäsite and was estimated to contain 740 t CeO_2, 510 t La_2O_3, 170 t Nd_2O_3; 62 t Pr_6O_{11}, and a small amount of other rare-earth oxides.

https://pubs.usgs.gov/of/2013/1072/OFR2013-1072.pdf

PRODUCTION

Salient Statistics—United States:	2012	2013	2014	2015	2016[e]
Production, bastnaesite concentrates	3,000	5,500	5,400	5,900	—
Imports:[2]					
Compounds:					
Cerium compounds	1,390	1,110	1,440	1,560	1,900
Other rare-earth compounds	3,400	7,330	9,110	7,640	10,000
Metals:					
Ferrocerium, alloys	276	313	378	356	290
Rare-earth metals, scandium, and yttrium	240	393	348	383	470
Exports:[2]					
Compounds:					
Cerium compounds	996	734	608	441	310
Other rare-earth compounds	1,830	5,570	3,800	4,530	350
Metals:					
Ferrocerium, alloys	960	1,420	1,640	1,220	220
Rare-earth metals, scandium, and yttrium	2,080	1,050	140	57	131
Consumption, estimated	15,000	15,000	17,000	17,000	16,000
Price, dollars per kilogram, yearend:[3]					
Cerium oxide, 99.5% minimum	10–12	5–6	4–5	2	2
Dysprosium oxide, 99.5% minimum	600–630	440–490	320–360	215–240	183–186
Europium oxide, 99.9% minimum	1,500–1,600	950–1,000	680–730	90–110	62–70
Lanthanum oxide, 99.5% minimum	9–11	6	5	2	2
Mischmetal, 65% cerium, 35% lanthanum	14–16	9–10	9–10	5–6	5–6
Neodymium oxide, 99.5% minimum	75–80	65–70	56–60	39–42	38–40
Terbium oxide, 99.99% minimum	1,200–1,300	800–850	590–640	410–470	410–425
Employment, mine and mill, annual average	275	380	391	351	—
Net import reliance[4] as a percentage of estimated consumption	80	63	68	65	100

https://minerals.usgs.gov/minerals/pubs/commodity/rare_earths/mcs-2017-raree.pdf

	Mine production[e] 2015	2016	Reserves[5]
United States	5,900	—	1,400,000
Australia	12,000	14,000	[6]3,400,000
Brazil	880	1,100	22,000,000
Canada	—	—	830,000
China	[7]105,000	[7]105,000	44,000,000
Greenland	—	—	1,500,000
India	1,700	1,700	6,900,000
Malaysia	500	300	30,000
Malawi	—	—	136,000
Russia	2,800	3,000	18,000,000
South Africa	—	—	860,000
Thailand[8]	760	800	NA
Vietnam[8]	250	300	22,000,000
World total (rounded)	130,000	126,000	120,000,000

World Resources: Rare earths are relatively abundant in the Earth's crust, but discovered minable concentrations are less common than for most other ores. U.S. and world resources are contained primarily in bastnäsite and monazite. Bastnäsite deposits in China and the United States constitute the largest percentage of the world's rare-earth economic resources, and monazite deposits constitute the second largest segment.

Substitutes: Substitutes are available for many applications but generally are less effective.

https://minerals.usgs.gov/minerals/pubs/commodity/rare_earths/mcs-2017-raree.pdf

Operating REE Mines

USGS

USGS OF2011-1189

China

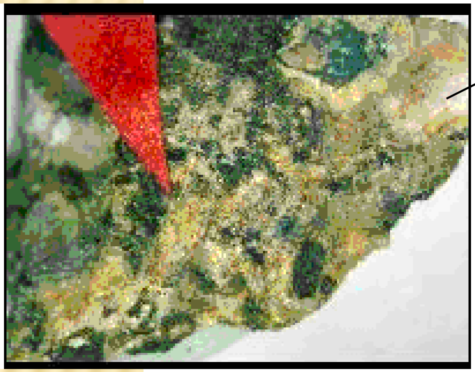
There are about 24 Chinese rare earth mining companies and 100 rare earth enterprises for separating, smelting and refining in China (Schüler et al. 2011). The Chinese industry is undergoing consolidation – mergers and acquisitions by large companies and the closing of small plants. Important rare earth mining companies in China are:

Companies in China	Share of world production [%]
Baotou Iron and Steel and Rare Earth Co. (Baogang Group)	~ 40
Minmetals Ganzhou Rare Earth Co. Ltd.	~ 25
Guangdong Zhujiang Rare Earths Co., Ltd.	~ 4
Hezhou Jinguang Rare Earth New Materials	~ 2
Shanghai Yaolong Nonferrous Metals Co.	~ 1.5
Jiangxi Rare Earths Co. (<1%)	< 1
Aluminum Corporation of China Limited (Chinalco)	

Important rare earth mining companies apart from China are:

Companies	Share of world production [%]
Molycorp Minerals LLC (Rare Earths Acquisitions LLC) **(USA)**	1.4
Lovozerskaya GOK **(Russia)**	1.4
Indian Rare Earths Limited **(India)**	< 1
Indústrias Nucleares do Brasil (INB) **(Brazil)**	

Rare Earth Elements



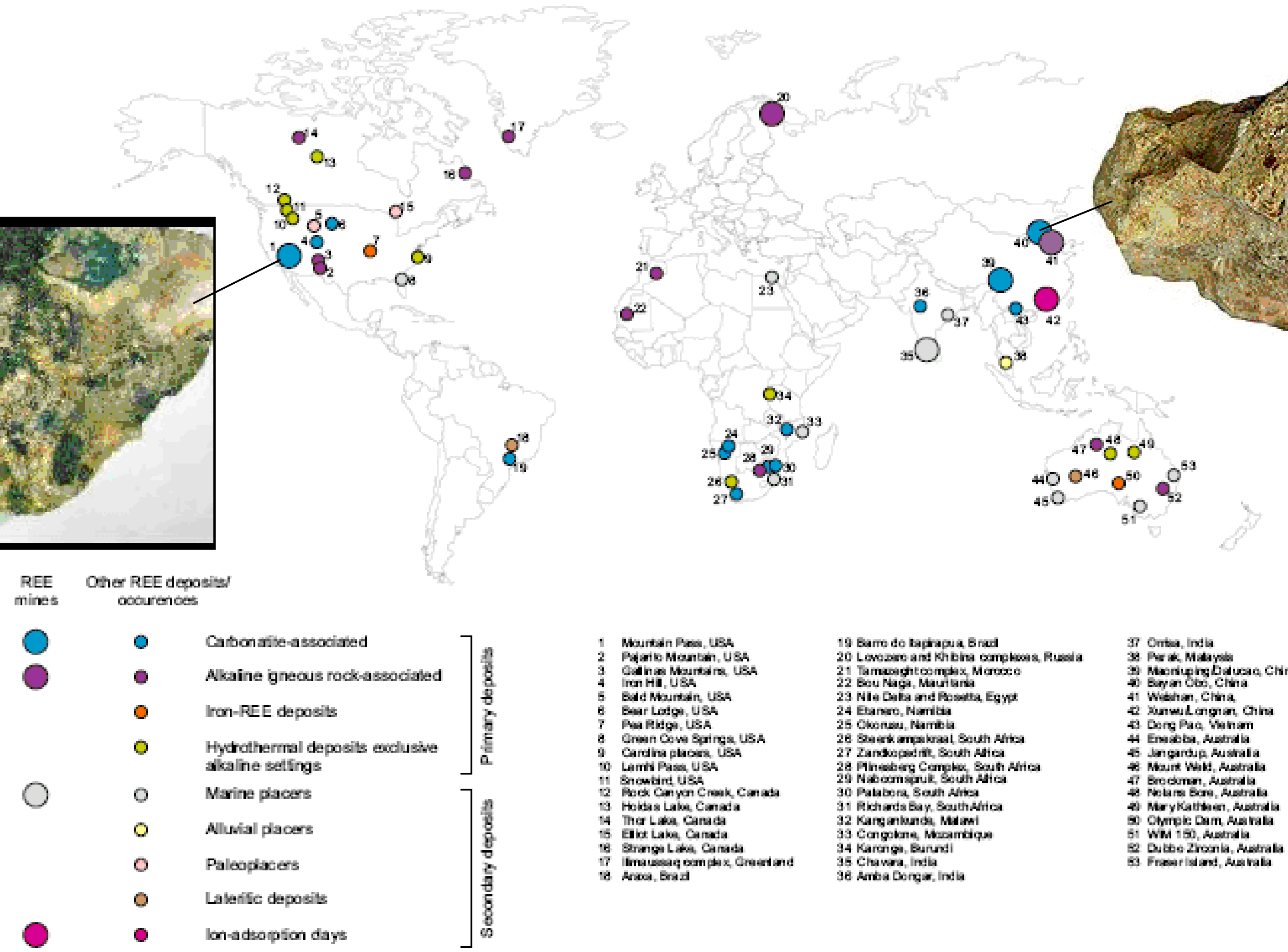
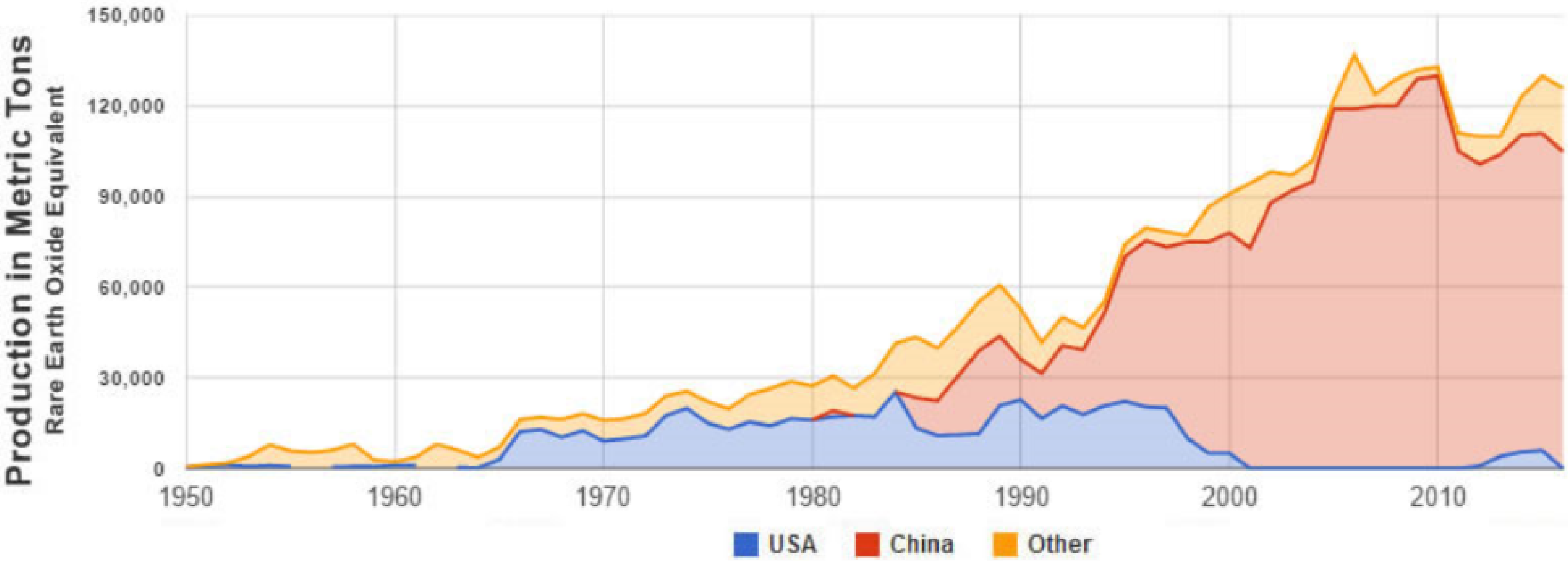


Figure 1 Map showing the global distribution of REE deposits.

www.MineralsUK.com

REE - Rare Earth Elements and their Uses

The demand for rare earth elements has grown rapidly, but their occurrence in minable deposits is limited.



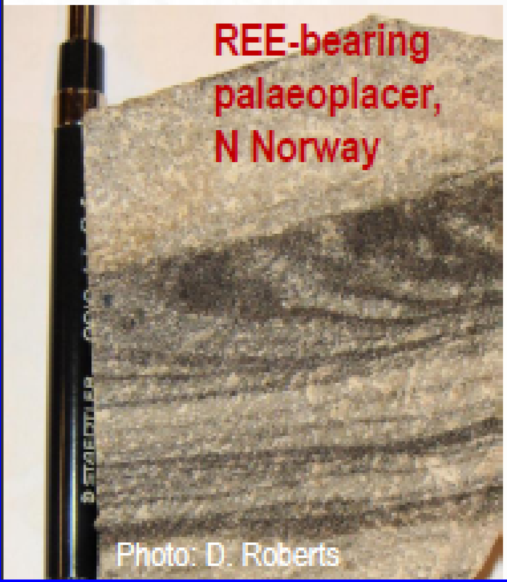
Rare Earth Element Production: This chart shows a history of rare earth element production, in metric tons of rare earth oxide equivalent, between 1950 and 2016. It clearly shows the United States' entry into the market in the mid-1960s when color television exploded demand. When China began selling rare earths at very low prices in the late-1980s and early-1990s, mines in the United States were forced to close because they could no longer make a profit. When China cut exports in 2010, rare earth prices skyrocketed. That motivated new production in the United States, Australia, Russia, Thailand, Malaysia, and other countries. In 2016, rare earth production in the United States stopped as the only remaining mine was put on care and maintenance.

USGS SIR10-5220

Rare Earth Elements

Ytterby mine, Sweden
Photo: Wikipedia

Yttrium, erbium, terbium and ytterbium all have their names from Ytterby: also holmium, thulium and gadolinium were first discovered in minerals from Ytterby.



REE-bearing palaeoplacer, N Norway

Photo: D. Roberts

- **World production** was 123 000 t in 2010 (BGS, 2011)
- REE are not so rare (0,3 – 64 g/t in the crust), except Pm
- The ores contain several REE (usually also U and Th): processing is challenging
- **554** projects outside China, few in Europe outside Norden, NW Russia
- **Main uses**: Catalysts, magnets, metallurgical applications, phosphors ++ Several REE have properties which are uniquely important in a wide range of high-tech applications.

Potential in Europe includes:

- REE in alkaline intrusions, carbonatites, skarn, + related pegmatites, e.g. Norra Kärr (Sweden) – **60 Mt @ 0.54% TREO + 1.72% ZrO_2**
- REE in apatite (e.g. Kiruna (Sweden) – study in progress)
- Beach sands (e.g. Peramos (Greece) - **5.7 Mt @ 1.17 % REE**)
- New deposit types, e.g. palaeoplacers
- Lovozero (Kola Peninsula) (reserves **>200 Mt @ >1.2% REE**) is in ?sporadic production

Project	Owner	Asset Location	Listing	Market Cap (US$M)	Resources (REO)	Stage	Capacity (REO tpa)	Start Up
Kvanefjeld	**Greenland Minerals & Energy**	Greenland	ASX	$150	10.3Mt	Feasibility	44,000+	2016
Mountain Pass	**Molycorp**	CA, USA	NYSE	$1,100	1.8 Mt	Commissioning	37,000	2012
Mt Weld	**Lynas Corp**	WA, Australia	ASX	$1,200	1.8 Mt	Construction	21,000	2012
Nechalacho	**Avalon Rare Metals**	NT, Canada	TSX	$200	4.35 Mt	Feasibility	8,000	2016
Strange Lake	**Quest**	QC, Canada	TSX-V	$75	2.4 Mt	Exploration	12,500	2017+
Zandkopsdrift	**Frontier**	South Africa	TSX-V	$70	0.94 Mt	Feasibility		2017
Nolans	**Arafura**	NT, Australia	ASX	$60	1.7 Mt	Feasibility	10,000	2017?
Dubbo Zirconia	**Alkane Resources**	NSW, Australia	ASX	$290	0.5 Mt	Feasibility	2,600	2015
Steenkampskraal	**Great Western Minerals Group**	South Africa	TSX-V	$115	0.03Mt	Construction	2,700	2013?

http://www.australianrareearths.com/images/rees-by-company-country-ex-china.gif

Global Rare Earth Deposits

Deposit	Location	Owner	Status	In-situ	TREO	HREO	Ratio
Kangankunde	Malawi	LYC	Inf	2.5mt	107,019	759	0.7%
Steenkampskraal	Sth Africa	GWG	Hist	0.3mt	29,125	2,246	7.7%
Hoidas Lake	Canada	GWG	M+Ind+Inf	2.9mt	68,400	2,563	3.7%
Eco Ridge	Canada	GEM	Ind+Inf	47.4mt	66,402	5,218	7.9%
Sarfartoq	Greenland	HUD	Inf	14.1mt	216,946	5,623	2.6%
Mountain Pass	USA	MCP	M+Ind+Inf	31.6mt	2,066,525	9,466	0.5%
Bokan	Alaska	UCU	Inf	3.7mt	27,525	10,530	38.3%
Bear Lodge	USA	RES	Inf	21.2mt	795,000	20,691	2.6%
Kutessay II	Kyrgyzstan	HRE	Inf	18.0mt	46,800	25,000	53.4%
Nolans Bore	Aust	ARU	M+Ind+Inf	46.0mt	1,150,000	35,995	3.1%
Zeus (Kipawa)	Canada	MAT	Ind+Inf	24.5mt	101,957	36,551	35.8%
Hastings	**Aust**	**HAS**	**Ind+Inf**	**36.2mt**	**76,020**	**65,160**	**85.7%**
Zandkopsdrift	Sth Africa	FRO	Inf	43.7mt	944,568	69,968	7.4%
Mt Weld	Aust	LYC	M+Ind+Inf	23.9mt	1,888,100	88,578	4.7%
Eldor	Canada	CCE	Inf	117.3mt	2,041,716	104,433	5.1%
Dubbo	Aust	ALK	Ind+Inf	73.2mt	651,480	167,960	25.8%
Norra Karr	Sweden	TSM	Inf	60.5mt	332,750	175,450	52.7%
Nechalacho	Canada	AVL	Ind+Inf	315.0mt	4,284,000	660,206	15.4%
Strange Lake	Canada	QRM	Ind+Inf	229.8mt	2,091,180	853,860	40.8%
Kvanefjeld	Greenland	GGG	Ind+Inf	861.0mt	9,212,700	1,103,802	12.0%

Owner	Stock Exchange Ticker Code (ASX and TSX)
Status	M = Measures, Ind = Indicated, Inf = Inferred, Hist = Historical
In-situ	Ore Tonnes
TREO	Total Rare Earth Oxides (Contained)
HREO	Heavy Rare Earth Oxides (Contained)
Ratio	Ratio of HREO to TREO
	HREO Deposit (Ratio greater than 30%)

http://www.australianrareearths.com/known-rees-resources-reserves.html

https://pubs.usgs.gov/of/2013/1072/OFR2013-1072.pdf

James Kennedy ThREE consulting Inc.
http://threeconsulting.com/pdfs/SME2017WebV.pdf

OTHER ISSUES

https://fas.org/sgp/crs/natsec/R41347.pdf

DEMAND

NOT ALL REE ARE EQUAL

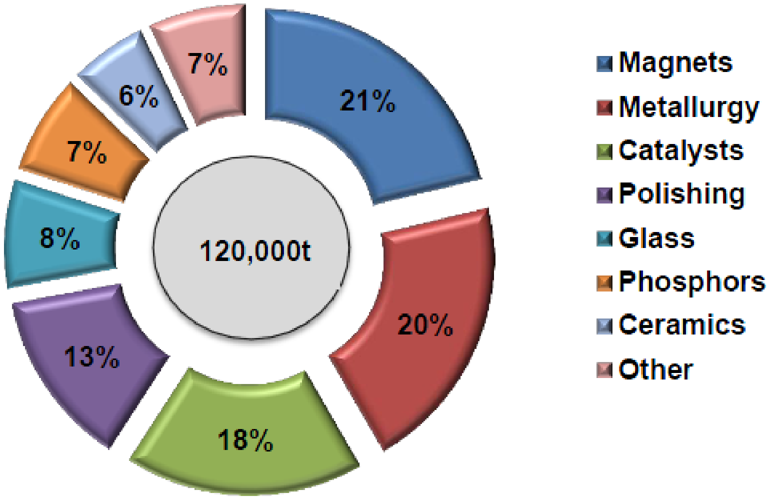
AND

GOOD SUBSTITUTIONS FOR REE USED IN MODERN TECHNOLOGY DO NOT EXIST

Global demand for rare earths by end-use in 2012

- World ‘official’ production of REO ~110,000t in 2012, 85-90% in China
- World demand ~120,000t in 2012, 65-70% in China

World: Demand for rare earths by end-use, 2012 (%)



Source: Roskill estimates

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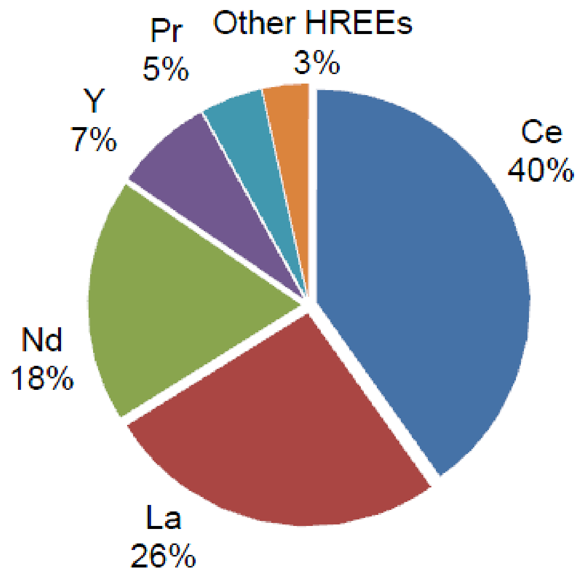
Demand for rare earths by element in 2012

Other HREEs
magnets, lasers, phosphors, glass, metallurgy, other

Pr
magnets, phosphors, ceramics, metallurgy, polishing, other

Y
phosphors, ceramics, other



Ce
polishing, metallurgy, catalysts, glass, phosphors, ceramics, other

La
metallurgy, catalysts, glass, phosphors, ceramics, polishing, other

Nd
magnets, ceramics, metallurgy, glass, catalysts, phosphors, other

Source: Roskill estimates

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Forecast Rates of Growth 2010-2020

Forecast Rare Earths Sector Rates of Growth 2010-2020			
Application	Growth 2010-2015	Growth 2015-2020	Comments
Catalysts	3-5%pa	3-5%pa	Growth rate unchanged through the decade.
Glass	Negligible	Negligible	Negligible growth rate as use in television and computer screens falling off rapidly.
Polishing	7-10%pa	8-12%pa	Until recently growth was forecast at 4-8%pa, but with increasing use in nano-particulate polishing powders for the electronic industry growth has been strong.
Metal Alloys	8-12%pa	4-8%	From 2010 to 2015 growth will be driven by the use of NiMH batteries in hybrid vehicles. IMCOA is of the view that meaningful substitution of hybrids by electric vehicles driven by Li-ion batteries will not occur before 2015/16.
Magnets	10-15%pa	10-15%pa	The real driver of demand in the next decade; price and availability a constraint. Could be greater than the indicated forecast if more of the rare earths used in permanent magnets were to become available.
Phosphors	6-10%pa	3-6%pa	New lighting devices under development use less rare earths, even though television and computer screens are getting bigger and being replaced more often.
Ceramics	6-8%pa	4-8%pa	Steady growth rates at historic rates.
Other	6-8%pa	4-8%pa	Barring the development of a new application with a high demand; steady growth rates at historic rates. Use of gadolinium for refrigeration is included.

https://fas.org/sgp/crs/natsec/R41347.pdf

https://fas.org/sgp/crs/natsec/R41347.pdf

FORECAST DEMAND FOR RARE EARTHS APPLICATIONS*

Application of separated Rare Earths products	2014 Demand Tonnes REO
Neodymium Rare Earths magnets	49,600
Nickel Metal Hydride battery alloy	32,500
Metallurgy applications excluding NiMH	12,700
Automotive catalytic convertors	12,200
Fluid Cracking Catalyst in oil refining	24,900
Glass polishing powder	20,600
Glass additives	7,800
Phosphors for lighting	10,800
Others	6,100
Total	**177,200**

* Forecasts are based on Lynas' current expectations and they are not guarantees of future events.

http://www.lynascorp.com/SiteCollectionDocuments/Fact%20Sheets/Rare_Earth_Applications.pdf

Key demand drivers and growth outlook

Sector	Segment	Sub Segments	Growth rate over GDP	Rare Earths used
Conventional Energy	Fuel Cracking Emissions control Nuclear	FCC Catalysts Material	+ 2%	La Ce Gd
Renewable Energy	Storage Wind turbines	NiMH Batteries Magnets	+10-15% +25-30%	La, Nd NdPr
Auto / Transportation	Emissions Control e-Mobility	Autocat Oxygen Sensors Magnets Batteries	+6-8% 0% +20-25% +20-25%	Ce Y NdPr, Dy La, Nd
Lighting	TC Lamps LEDs	Phosphors	+5%	Eu, Tb, Y, Ce, La
Metallurgy	Special Alloys	RE Silicides	+10-15%	CeLa
Electronics	GHD Cameras Displays Capacitors & chips	Polishing Materials Phosphors	+2-5% +5-10% 0% 0%	CeLa La Eu, Tb, Y, Ce, La Dy, Nd, Ce
Medical	MRI PET Scans Medicines	Magnets Crystals Material	+5-10% +10-15% +10-15%	Gd, NdPr Lu La
Miscellaneous	Defense Decorative Ceramics Agriculture	Niches		NdPr, Dy, La Ce, Pr Ce

Looming crisis - Rare Earths supply will be outstripped by demand; 115kt REO in 2010

CHINESE SUPPLY SOURCES (2010 CAPACITY, REO)

Baotou — **55,000t**
- By product of iron ore mine
- Moving to higher grade iron, with lower impurities and Rare Earths
- Tailing facilities near capacity

Sichuan — **10,000t**
- Jiangxi Copper to invest ¥1.2Bn
- Target to increase value added
- Capacity expected to increase

Ionic clay regions — **35,000t**
- Reportedly 14 yrs of resource
- Large amount of illegal mining
- Government action taking effect

Recycling — **3,300t**

Total — **103,300t**

NON CHINESE SUPPLY SOURCES (2010 CAPACITY, REO)

India — **3,000t**
- Subsidiary of Indian AEA
- Toyota Tsusho bought trading firm with Japanese distribution

Russia — **4,000t**
- Limited expansion capacity
- By product of Mg production

Recycling — **1,500t**
- Magnet swarf
- Batteries – future potential

USA – Mountain Pass — **3,000t**
- Reprocessing stockpiles
- Requires approx. US$530 million rebuild

Total — **11,500t**

Source: Industry resources and Lynas research

Our assumptions show global supply at 170kt by 2014, compared to demand of 190kt

2014 FORECAST SUPPLY ASSUMPTIONS

SUPPLY SOURCES

• Baotou	60,000t
• Sichuan	20,000t
• Ionic Clay Regions	30,000t
• Recycling in China	4,000t
China Total	**114,000t**
• Mount Weld	22,000t
• Mountain Pass	20,000t
• Others (India & Russia)	12,000t
• Recycling outside China	1,800t
Outside China Total	**55,800t**
Grand Total	**169,800t**

KEY UNDERLYING ASSUMPTIONS

- Baotou – 10% production increase 2010 / 2014
- Sichuan – full production quota to be utilised
- Iconic Clay – 2010 reduced from 2008 reported levels due to news reports. 2014 reduced to double current production quota (conservative estimate, could be lower)
- Mountain Pass – full production (20,000tpa) achieved
- Recycling – 20% Nd, Pr & Dy recycled from previous year's magnet production (~30% SWARF losses)

Lynas CORPORATION LTD

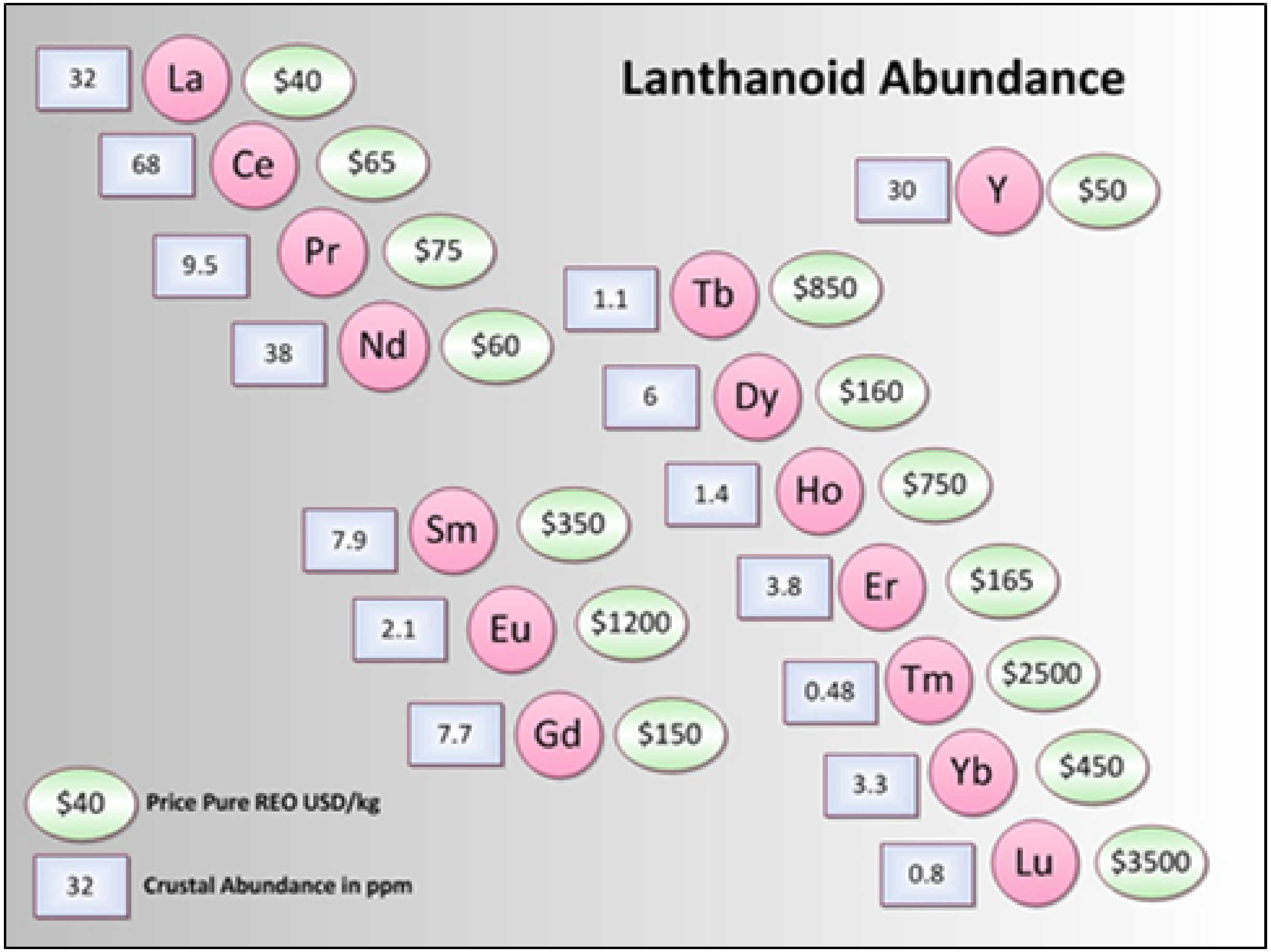
Table 1.2: Range of projected surpluses / deficits for select REOs

	2010e	2011p	2012p	2013p	2014p	2015p	2016p	2017p
La_2O_3	O	O	O	✔	✔ ✔	✔ ✔	✔ ✔ ✔	✔ ✔ ✔
CeO_2	O	O	O	✔	✔ ✔	✔ ✔ ✔	✔ ✔ ✔	✔ ✔ ✔
Nd_2O_3	✘	✘	✘	O	O	✔	✔ ✔	✔ ✔ ✔
Eu_2O_3	✘ ✘	✘ ✘	✘ ✘	✘ ✘	✘	O	✔ ✔	✔ ✔
Tb_4O_7	✘	✘	✘	✘	✘	O	✔ ✔	✔ ✔ ✔
Dy_2O_3	✘ ✘	✘ ✘	✘ ✘	✘ ✘	✘ ✘	✘ ✘	O	✔
Y_2O_3	✘ ✘	✘ ✘	✘ ✘	✘ ✘	✘ ✘	✘	✔	✔ ✔
CREO	✘	✘	✘	✘	✘	✔	✔ ✔	✔ ✔ ✔

Supply as % demand: ✘ ✘ = 50-74% : ✘ = 75-94% : O = 95-105% : ✔ = 106-125% : ✔ ✔ = 126-150% : ✔ ✔ ✔ ≥ 151%

CREO = oxides of Nd, Eu, Tb, Dy & Y

Source: TMR estimates / projections



Prices are for pure oxides from a leading rare earth elements chemical producer in 2009. Pm (prometheum) is not shown because it does not occur in nature and is not commercially available.

REO: rare earth oxide.

USD/kg: United States Dollars per kilogram.

USGS
OF2011-1189

ECONOMICS REE

RARE EARTH ELEMENTS—MINERALOGY

- 270 minerals
- Bastnaesite $LnFCO_3$
- Apatite > 5400 ppm total REE $Ca_5(PO_4)_3(OH,F,Cl)$
- monazite 500,000 ppm total REE $(Ln,Th)PO_4$
- manganese nodules 99,000 ppm total REE

TABLE 2

RARE EARTH CONTENTS OF SELECTED SOURCE MINERALS[1,2]

(Percent of total rare-earth oxide)

Rare earth	Bastnäsite: Mountain Pass, CA, United States[3]	Bastnäsite: Bayan Obo, Nei Mongol, China[4]	Monazite: Mount Weld, Australia[5]	Monazite: Nangang, Guangdong, China[6]
Yttrium	0.10	trace	trace	2.40
Lanthanum	33.20	23.00	26.00	23.00
Cerium	49.10	50.00	51.00	42.70
Praseodymium	4.34	6.20	4.00	4.10
Neodymium	12.00	18.50	15.00	17.00
Samarium	0.80	0.80	1.80	3.00
Europium	0.10	0.20	0.40	0.10
Gadolinium	0.20	0.70	1.00	2.00
Terbium	trace	0.10	0.10	0.70
Dysprosium	trace	0.10	0.20	0.80
Holmium	trace	trace	0.10	0.12
Erbium	trace	trace	0.20	0.30
Thulium	trace	trace	trace	trace
Ytterbium	trace	trace	0.10	2.40
Lutetium	trace	trace	trace	0.14
Total	100	100	100	100

Rare earth	Loparite: Revda, Murmansk Oblast, Russia[7]	Rare earth laterite: Xunwu, Jiangxi Province, China[8]	Rare earth laterite: Longnan, Jiangxi Province, China[8]	Xenotime: Southeast Guangdong, China[9]
Yttrium	1.30	8.00	65.00	59.30
Lanthanum	25.00	43.40	1.82	1.20
Cerium	50.50	2.40	0.40	3.00
Praseodymium	5.00	9.00	0.70	0.60
Neodymium	15.00	31.70	3.00	3.50
Samarium	0.70	3.90	2.80	2.20
Europium	0.09	0.50	0.10	0.20
Gadolinium	0.60	3.00	6.90	5.00
Terbium	trace	trace	1.30	1.20
Dysprosium	0.60	trace	6.70	9.10
Holmium	0.70	trace	1.60	2.60
Erbium	0.80	trace	4.90	5.60
Thulium	0.10	trace	0.70	1.30
Ytterbium	0.20	0.30	2.50	6.00
Lutetium	0.15	0.10	0.40	1.80
Total	100	100	100	100

[1]Data are rounded to no more than three significant digits; may not add to totals shown.

[2]Rare earths are listed in order of atomic number.

http://minerals.usgs.gov/minerals/pubs/commodity/rare_earths/myb1-2012-raree.pdf

Rare Earth Element Minerals & Deposit Types

Group-Mineral	Formula	Carbonatite	Alkaline Intrusion-Related	Placer	Phosphorite
Oxides					
Aeschynite	$(Ln,Ca,Fe)(Ti,Nb)_2(O,OH)_6$		X		
Euxenite	$(Y,Ln,Ca)(Nb,Ta,Ti)_2(O,OH)_6$		X	X	
Fergusonite	$YNbO_4$		X		
Carbonates					
Bastnäsite	$(Ln,Y)CO_3F$	X	X		
Parisite	$Ca(Ln)_2(CO_3)_3F_2$	X	X		
Synchisite	$Ca(Ln,Y)(CO_3)_2F$	X	X		
Tengerite	$Y_2(CO_3)_3 \bullet n(H_2O)$		X		
Phosphates					
Apatite	$(Ca,Ln)_5(PO_4)_3(OH,F,Cl)$	X	X		X
Monazite	$(Ln,Th)PO_4$	X	X	X	
Xenotime	YPO_4		X	X	
Silicates					
Allanite	$(Ln,Y,Ca)_2(Al,Fe^{3+})_2(SiO_4)_3(OH)$		X		
Eudialyte	$Na_4(Ca,Ce)_2(Fe^{2+},Mn^{2+},Y)ZrSi_8O_{22}(OH,Cl)_2$		X		
Thalenite	$Y_2Si_2O_7$		X		
Zircon	$(Zr,Ln)SiO_4$		X	X	

USGS science for a changing world

Ln: Lanthanide (a.k.a. REE)

REE ORES

- REE ores contain all rare earth elements except Pm
- There is no shortage of REE ores

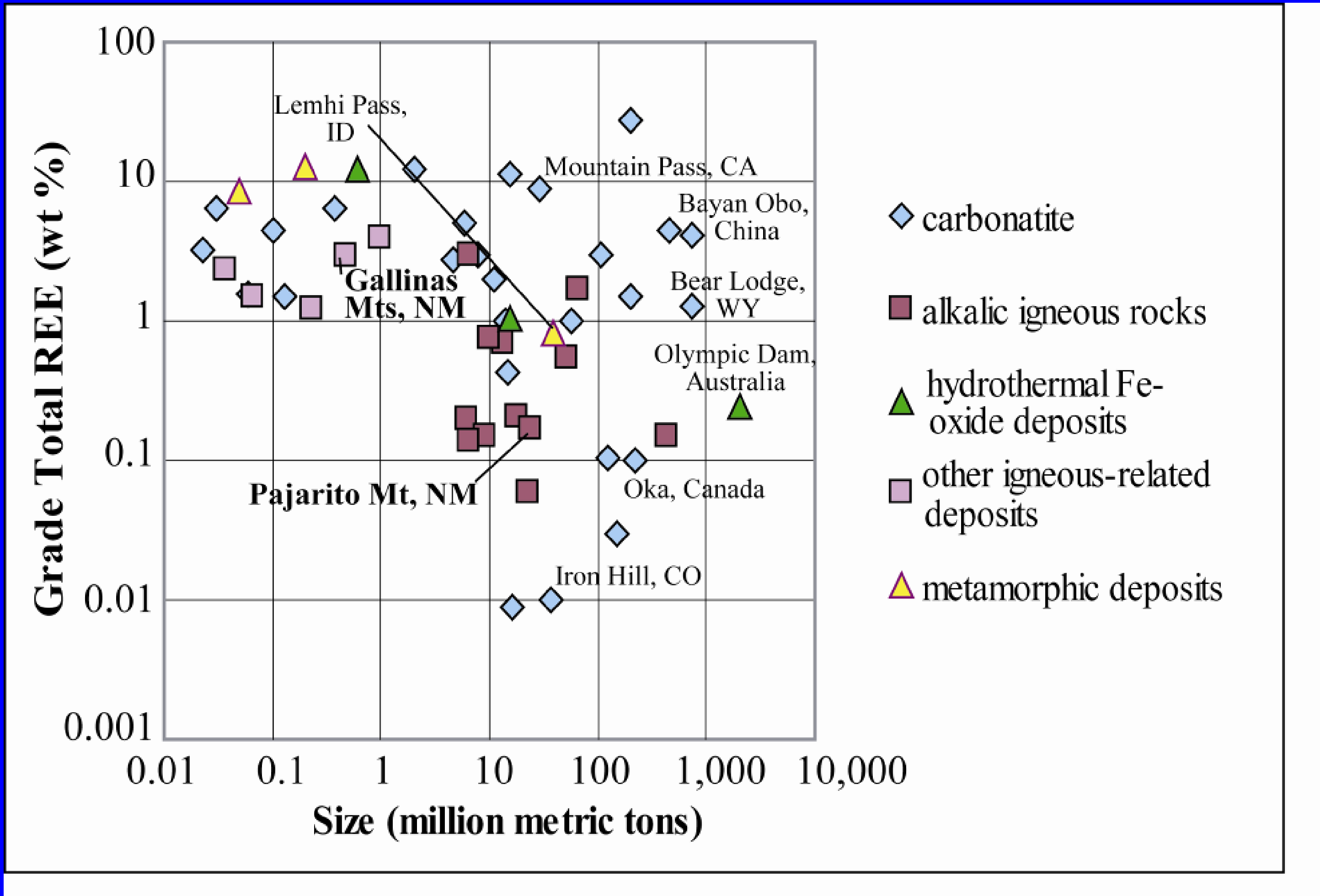
  Most rare earths are not rare
- Most ores are rich in Ce, La, Nd and Pr
- The rare earths are chemically very similar
- Producers try to balance supply and demand

  And are *rarely* successful!

Commodity	US production 2009 mt	World production 2009 mt	consumption 2009 mt	Price 2009	World reserves 2009 mt
Cu	1,190,000	15,800,000	1,660,000	$2.3/lb	540,000,000
Au	210	2,350	170	$950/oz	47,000
REO	0	124,000	7,410	varies	99,000,000
Be	120	140	140	$120/lb	15900+
Sb	0	187,000	22,400	$2.3/lb	2,100,000
As	385	52,500	3,600	$0.92/lb	1,070,000
Bi	100	7,300	1,020	$7.4/lb	320,000
Ga	0	78	20	$480/kg	1,000,000
Ge	5	14	5	$950/kg	450+
Te	W		W	$145/kg	22,000
cement	71,800,000	2,800,000,000	73,800,000	$100/mton	

Deposit	Location	Size (tons REE)	Grade % REE	Type of deposit
Bayan Obo	Inner Mongolia	48,000,000	6	Carbonatite and/or Fe oxide-Cu-Au
Mountain Pass	California	1,800,000	8.9	Carbonatite
Mount Weld	Australia	1,700,000	11.2	Carbonatite laterite
Dubbo	Australia	700,000	0.86	trachyte
Thor Lake	NW Territories, Canada	1,547,000	0.41	Alkaline rock
Strange Lake	Laborador, Quebec	440,000	0.85	Alkaline rock

Deposit		Tonnage (metric tons)	Grade (percent TREO)	Contained TREO (metric tons)	Source
Reserves—Proven and probable					
Mountain Pass,	California	13,588,000	8.24	1,120,000	Molycorp, Inc. (2010).
Resources—Inferred					
Bear Lodge,	Wyoming	10,678,000	3.60	384,000	Noble and others (2009).
Resources—Unclassified					
Bald Mountain,	Wyoming	18,000,000	0.08	14,400	Osterwald and others (1966).
Bokan Mountain,	Alaska	34,100,000	0.48	164,000	Keyser and Kennedy (2007).
Diamond Creek,	Idaho	5,800,000	1.22	70,800	Staatz and others (1979).
Elk Creek,	Nebraska	39,400,000			Molycorp, Inc. (1986).
Gallinas Mtns.,	New Mexico	46,000	2.95	1,400	Jackson and Christiansen (1993).
Hall Mountain,	Idaho	100,000	0.05	50	Staatz and others (1979).
Hick's Dome,	Illinois	14,700,000	0.42	62,000	Jackson and Christiansen (1993).
Iron Hill,	Colorado	2,424,000,000	0.40	9,696,000	Staatz and others (1979).
Lemhi Pass,	Idaho	500,000	0.33	1,650	Staatz and others (1979).
Mineville,	New York	9,000,000	0.9	80,000	McKeown and Klemic (1956).
Music Valley,	California	50,000	8.6	4,300	Jackson and Christiansen (1993).
Pajarito,	New Mexico	2,400,000	0.18	4,000	Jackson and Christiansen (1993).
Pea Ridge,	Missouri	600,000	12	72,000	Grauch and others (2010).
Scrub Oaks,	New Jersey	10,000,000	0.38	38,000	Klemic and other (1959).
Wet Mountains,	Colorado	13,957,000	0.42	59,000	Jackson and Christiansen (1993).



GRADE AND SIZE (TONNAGE) OF SELECTED REE DEPOSITS, USING DATA FROM ORIS AND GRAUCH (2002) AND RESOURCES DATA FROM SCHREINER (1993) AND JACKSON AND CHRISTIANSEN (1993) FOR THE GALLINAS MOUNTAINS. DEPOSITS IN BOLD ARE LOCATED IN NEW MEXICO.